An Analysis of Large Displacement Pneumatic Slug Tests for the Characterization of Aquifer Parameters – Guidelines for an Alternative Field Procedure

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An Analysis of Large Displacement Pneumatic Slug Tests for the Characterization of Aquifer Parameters – Guidelines for an Alternative Field Procedure

by

Madison E. Wayt

A thesis submitted to the Graduate College in partial fulfillment of the requirements for the degree of Master of Science Geological and Environmental Sciences Western Michigan University April 2020

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Variations in hydraulic conductivity (K) between larger scale aquifer tests and smaller scale slug tests, and within individual aquifer tests, have been linked to method bias and aquifer heterogeneity. The impacts of varying slug sizes on K, which represents K dependence on a smaller scale, is not as well understood. To examine the relationship between K and slug size, a series of slug tests with a range of initial displacements were performed in three intermediate to high K, unconfined aquifers encompassing homogeneous, mildly heterogeneous, and moderate to highly heterogeneous conditions. Slug test estimated K values at Asylum Lake are compared to K values derived from a 28-hour aquifer pumping test to examine for method bias. A statistically significant increase in hydraulic conductivity with decreasing scale, or in this case slug size, was only found at the Grand Rapids site and is likely related to turbulent energy loss in the porous media surrounding the well screen for the largest slugs. Additionally, a series of multi-well pneumatic slug tests were performed at Asylum Lake in hopes of obtaining reliable storage parameters comparable to an aquifer pumping test and testing the effect of slug size on storage parameters. Results indicate that multi-well tests can produce reliable Ss estimates representative of the aquifer. Lastly, guidelines were developed for performing pneumatic slug testing in the field using a newly designed pneumatic slug unit.
I am very grateful to a number of people, without which this thesis could not have been accomplished. Only a few of whom I can specifically acknowledge here. I would like to thank Tanten Buszka, Chanho Park, Romeo Akara, and Tom Howe for their assistance in completing the field work for this study. I would like to thank all of the students who participated in the Hydrogeology Field Course who helped to collect aquifer test data. I would like to thank Dan Greene for providing me with the opportunity to perform tests at both the Muskegon and Grand Rapids Sites and for sharing his knowledge of slug tests. I would like to thank Glenn Duffield for his insight on data processing in AQTESOLV and helping us to solve several analysis roadblocks. I would especially like to express sincere gratitude for Dr. Matt Reeves - his continuous help and guidance not only on this project, but also on my future career. And lastly, I would like to thank my family for their moral support during the completion of this thesis. My mom, and especially my dad, who I would not be here without, my sister who always lifts my spirits and inspires me to be my best, and James Smith who is my rock and whom I would not have finished this thesis without.

Madison Wayt
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Aquifer Parameters

Hydrogeologists assess the occurrence, availability, and quality of groundwater. If water quality is sufficient, the value of an aquifer depends largely on two intrinsic characteristics that describe the ability of the aquifer to both store and transmit water: aquifer storativity and transmissivity (Ferris et al., 1962; Bear, 1972). Transmissivity, \( T \) [L\(^2\)/T] is defined as the product of hydraulic conductivity, \( K \) [L/T], and aquifer thickness, \( B \) [L]. Hydraulic conductivity describes the ability of a porous medium to transmit water, and is formally defined in Darcy’s Law as a property of the porous medium that relates volumetric discharge to the hydraulic gradient (Fetter, 2001):

\[
Q = -KA \frac{dh}{dl}
\]

where \( Q \) [L\(^3\)/T] is volumetric discharge, \( A \) [L\(^2\)] is area cross-sectional to flow, and \( dh/dl \) [dimensionless] is the hydraulic gradient. Storativity (\( S \)), the product of specific storage \( S_s \) [1/L] and aquifer thickness, is a dimensionless parameter that describes the release of water attributed to aquifer compressibility and the expansion of water as fluid pressure decreases. Unconfined aquifers have an additional storage mechanism not present in confined aquifers termed specific yield, \( S_y \) [dimensionless], that accounts for the drainage of pore water by gravity with decline of the water table (Fetter, 2001). Specific yield is a fraction of total porosity and ranges from 0.10 to 0.40 (Anderson and Woessner, 1992). These values are considerably larger than contributions from specific storage in unconfined aquifers which range from \( 1.0 \times 10^{-3} \) – \( 5.0 \times 10^{-5} \) m\(^{-1}\) (Domenico and
Storativity is important for transient groundwater problems as best described in the groundwater flow equation, which combines the conservation of both fluid mass and fluid momentum (i.e., Darcy’s law). The groundwater flow equation for two-dimensional unconfined flow through a homogeneous and isotropic aquifer is (Fetter, 2001):

$$\frac{\partial}{\partial x} \left( h \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( h \frac{\partial h}{\partial y} \right) = \frac{S_y}{K} \frac{\partial h}{\partial t}$$

where $S_y$ is specific yield, $K$ is hydraulic conductivity, and $h$ is saturated thickness (assuming $h$ is measured from the base of the aquifer).

Reliable estimation of aquifer parameters is essential for nearly any groundwater investigation, including groundwater allocation and policy, contaminant fate and transport, and remediation of contaminated sites. In these studies, hydraulic conductivity is the most significant parameter, and storage is of lesser importance and only plays a role in transient problems. This is reflected in the multitude of hydraulic test methods, all of which estimate hydraulic conductivity, but not all can be used to estimate storage. The most common methods for estimating $K$ differ by scale: permeameter testing of aquifer samples in the laboratory (core scale), borehole flowmeter and slug tests (near-well scale), and aquifer pumping tests (field to sub-regional scale) (Fetter, 2001; Zemansky et al., 2005; Paradis et al., 2016).

Estimates of $K$ derived from permeameter tests must be applied with extreme caution due to scale limitations and disruption of in-situ pore geometry through repacking aquifer sediment which can introduce significant error (Ferris et al., 1962). Previous work conducted by Melby (1989) and
Herzog et al. (1989) suggest that permeameters produce reasonable results for coarse, high permeability sediment, but are unreliable for fine-grained sediments and soils. Cleary (1990) concluded that the use of laboratory $K$ values in contaminant groundwater studies frequently leads to the underestimation of contaminant travel times (Cambel et al., 1990). Aquifer pumping and slug tests are performed in situ and estimate hydraulic properties over a considerably greater volume of aquifer than permeameter tests, and for these reasons, are generally considered more reliable. Analysis of multi-well aquifer pump test data yield estimates of both $S$ and $T$ (which are then used to estimate $S_s$ and $K$), whereas most slug test analysis exclusively estimate $K$, except for Cooper et al. (1967) and Hyder et al. (1994) which provide estimates of both $K$ and $S_s$.

### Aquifer Pumping Tests and Slug Tests

Aquifer pumping tests and slug tests are the primary field methods used to obtain in situ estimates of the transmissive properties of a formation (Kruseman and de Ridder, 1990; Butler, 1997). These two methods differ in the number of required wells, volume of the aquifer sampled, aquifer storage mechanisms (particularly for unconfined aquifers), and analytic models used for data analysis. This subsection provides general background and theory of aquifer pumping tests and slug tests.

Aquifer pumping tests apply stress to an aquifer in the form of extracting groundwater from a well and monitoring changes in water levels (i.e., drawdown) as a function of time to study aquifer response (Figure 1). Values of $T$ and $S$ are then estimated from these data by fitting an appropriate solution to the groundwater flow equation for radial flow to a pumping well given a set of assumptions that typically include aquifer homogeneity and isotropy (Theis, 1935). Hydraulic conductivity is then determined by normalizing transmissivity by aquifer thickness, typically
defined from well logs. Since the duration of most aquifer pumping tests is on the order of hours to days, the aquifer volume sampled is considerably larger than a near-well slug test with shorter transience on the scale of seconds to minutes (Butler and Healey, 1998). Thus, aquifer tests are widely considered to provide the most representative bulk estimates of $K$.

Hvorslev (1951) established the use of slug testing for in situ determination of aquifer hydraulic conductivity. A slug test involves a near instantaneous change in water level in a well and measuring the recovery back to the pre-test static level. Recovery of water levels in a well requires that water move either into or out of the well, and the rate at which the recovery occurs is governed by $K$. The response data are used to estimate $K$ of the formation through comparisons with theoretical models of slug test solutions to the groundwater flow equation with or without storage (Butler, 1997). Slug tests radially sample the aquifer volume immediately surrounding the well. Larger slug displacements should naturally extend this radius further from the well, although

Figure 1: Aquifer pumping test schematic diagram (Fetter, 2001).
smaller physical slugs are commonly used in practice. It is generally accepted that the radius of influence of a slug test is small and provides a limited view of subsurface hydrogeologic properties near the well (Engard et al., 2015)

Quick and easy to perform, slug tests are preferred over aquifer pumping tests in: (1) sediments with lower $K$ values that are not conducive for constant-rate aquifer pumping tests (Campbell et al., 1990), (2) areas where contaminated water from an aquifer pump test would need to be treated prior to disposal, and (3) stream and lake beds. Costs and time of slug tests are also considerably less than aquifer pumping tests as they are performed on observation wells that are significantly cheaper to drill, install, and develop than a pumping-monitoring well network (Bouwer and Rice, 1976). Aquifer pumping tests are preferred for characterizing aquifers on larger spatial and time scales to determine: (1) the ability of an aquifer to produce and sustain large quantities of water, (2) interconnectivity of aquifer units, (3) hydraulic boundaries of a flow system, and (4) aquifer storage. Given sufficient resources, slug tests can be performed as a preliminary step to help guide the design of more comprehensive aquifer pumping tests (Black, 1978).

**Hydraulic Conductivity and the Scale Effect**

Previous studies by Bradbury and Muldoon (1990), Rovey and Cherkauer (1995), and Butler and Healy (1998) compared $K$ values derived from aquifer pumping and slug tests. Bradbury and Muldoon (1990) compared multiple techniques including aquifer pumping tests, specific capacity tests, slug tests, laboratory permeameter tests, and estimates based on particle-size distributions to measure $K$ in unconsolidated glacial and fluvial sediment. They concluded that estimated values of hydraulic conductivity tend to increase with the scale of measurement. Rovey and Cherkauer
(1995) estimated $K$ for five stratigraphic units in a carbonate aquifer with physical and pneumatic slugs, aquifer pumping tests, and two numerical models. Their study supports the findings of Bradbury and Muldoon (1990) that $K$ values derived from small-scale field measurements will generally be less than sub-regional to regional scale values. Rovey and Cherkauser (1995) further suggest that scaling effects are influenced by the type of geologic medium and degree of secondary porosity, with pronounced scaling effects attributed to preferential flow through fractures, gravel stingers, and other connected high $K$ units within an aquifer. Butler and Healy (1998) agree that $K$ estimates from aquifer pumping tests are, on average, considerably larger than estimates obtained from slug tests in the same formation. Instead of an underlying scale dependence in $K$, Butler and Healy (1998) suggest that $K$ values derived from slug tests are biased low, but for different reasons: incomplete well development, borehole skin and storage effects, and to a much lesser extent, failure to account for vertical anisotropy.

In professional practice, there is a tendency for slug tests to be viewed as a lower limit of $K$, particularly when compared to aquifer pumping tests. Scale effects can be observed in field data as well as hydraulic data generated in the lab and numerical models. Identifying if the scale effect reported by Bradbury and Muldoon (1990), Rovey and Cherkauser (1995) and Butler and Healy (1998) is related to the volume of aquifer tested, aquifer heterogeneity, or bias associated with the testing method, is the basis for work conducted by Makuch et al. (1999), Rovey (1997), and Makuch and Cherkauser (1998). Makuch et al. (1999) analyzed various types of sediments using laboratory- to regional-scale methods to determine if the scale effect is a function of the type of subsurface medium tested. They found no variations of $K$ with scale (scale determined from test
type) for homogenous media; however, increases in $K$ with scale were observed in heterogenous media.

Rovey (1997) developed MODFLOW models with various arrangements of heterogeneity to simulate field tests at different scales represented by the radius of influence. He found that radial hydraulic conductivity depends on the scale of measurement and determined the cause of the increase in hydraulic conductivity with scale to be a consequence of natural heterogeneity.

“Over short distances, water converging toward a borehole must generally flow across heterogeneities. Therefore, small-scale tests tend to measure a weighted harmonic mean of the $K$ field. Over a large area, however, flow is primarily along high $K$ heterogeneities. Therefore large-scale tests approach a weighted arithmetic mean where high $K$ heterogeneities have a greater influence (Rovey, 1997).”

To further prove that scale effect is not a consequence of testing method, Makuch and Cherkauer (1998) examined estimates of hydraulic conductivity obtained from individual aquifer pumping tests with scale defined as the total volume of water discharged. They postulated that if scale effects are observed using a single testing method, it proves that increases in $K$ with scale are caused by aquifer heterogeneity and method bias. Their findings indicate that estimates of $K$ generally evolve (increase) during an individual pumping test as the volume of aquifer impacted increases and conclude this scaling effect is a result of aquifer heterogeneity. Figure 2 shows results for four of the 22 aquifer tests conducted by Makuch and Cherkauer (1998) as well as their numerical modeling results. Results for all four field tests show an increase in estimated $K$ with increasing discharged volume of water; this trend was also observed in the numerical simulations, except for
homogeneous aquifer cases (Makuch and Cherkauer, 1998). For all tests, $K$ increases approximately an order of magnitude with equal increases in discharged volume.

Figure 2: The top four graphs show analysis field results for Tests 1-4 of the 25 individual aquifer pumping tests conducted by Makuch and Cherkauer (1998). Results for all four tests show increases in $K$ with discharged volume. The bottom graph shows numerical modeling results for a range hydrogeological scenarios. In all scenarios except the homogenous aquifer case, $K$ increases with volume of water discharged.
Variations in $K$ between larger-scale aquifer pumping tests and smaller scale slug tests, and within individual aquifer pumping tests as discussed above, have been covered extensively. However, the impacts of varying slug sizes on $K$, which describe $K$ dependence on a smaller, near-well scale, are relatively unknown. Previous studies completed by Alfaifi (2015) and Ismael (2016) compared $K$ values derived from physical slugs of different size. Alfaifi (2015) compared two sizes of physical slug rods, one half of the well diameter, and one three quarters the well diameter and found that the larger slug produced larger $K$ values regardless of the analysis method applied. Ismael (2016) performed slug tests using slug rods of different length and diameter. He was unable to reproduce the results of Alfaifi (2015) and found no statistically significant increases in estimated $K$ with slug size. However, he did find that flow direction (slug-in verses slug-out) influenced estimated $K$ values, with slug-in tests producing significantly larger $K$ estimates than slug out tests.

**Types of Slug Tests**

The instantaneous change in head required for a slug test can be accomplished by adding or removing a slug in the form of a solid object (physical slug), water, or air (pneumatic slug). A physical slug is the most common method used in practice for initiating a slug test. This involves displacement of water in the well using a solid slug which is typically a piece of stainless steel or PVC pipe filled with sand or similar material and capped at both ends. A hook or loop on one of the caps allows for the attachment of a rope or cable for lowering and raising the slug within the well (Butler, 1997).
Over the past decade, the pneumatic approach for test initiation has become increasingly popular. This method, which was first fully described in the groundwater literature by Prosser (1981), involves pressurizing the air column in a sealed well by injecting compressed air or nitrogen gas to depress the water column for a positive displacement slug test. Conversely, a negative displacement slug test involves decreasing the pressure in the sealed well using a vacuum pump to increase water levels. Pneumatic slug testing allows for either a rise (vacuum) or decrease (positive pressure) of the water column as water is driven into or out of the well in response to the change in pressure in the air column, respectively (Figure 3). Once the pressure in the well is stabilized, the total displacement in the well is equal to the magnitude of the pressure head of the air column. Maximum displacements are limited by either: (1) the distance from the top of the well above the top of the water column in the well for negative displacement slugs, or (2) the distance from the top of the water column to the top of the well screen for positive displacement slugs (Reeves et al., 2020).
Figure 3: Physical and pneumatic slug test schematic diagrams (Robins, 2016).
Pneumatic Slug Tests – Advantages and Limitations

Pneumatic slug testing provides several advantages over physical slugs. First, pneumatic methods greatly exceed the ability of solid slugs to generate perturbations that extend beyond the disturbed zone of a well and ensure that measured responses are representative of the aquifer. A pneumatic slug also allows for considerable flexibility as initial displacements can be selected along a continuum ranging from small perturbations equivalent to small solid slugs up to a maximum that is generally greater than can be achieved using solid slugs. Second, pneumatic slugs provide the closest approximation that is practically possible to the instantaneous water level change assumption used in all analytical slug test solutions (e.g., Hvorslev, 1951; Butler, 1997). For this reason, pneumatic slug data are typically cleaner and exhibit less noise than solid slugs. Lastly, pneumatic slugs only require a pressure transducer and cable to be in contact with contaminated water, and this greatly simplifies decontamination protocols (Reeves et al., 2020).

Limitations and potential sources of error can be introduced during pneumatic slug testing. Unlike solid slugs, pneumatic slugs cannot be used in wells that are screened across the water table as the air will be either pulled from the unsaturated zone during vacuum tests or pushed into the aquifer during positive pressure tests. This will be apparent in the field as wells screened across the water table cannot be pressurized. Discrepancies between slug size and initial displacement based on gauge pressure and recorded water level data in the field can occur in high $K$ aquifers (Reeves et al., 2020). In this case, recorded water level data should be used over the gauge reading. Skin effects in poorly developed monitoring wells can also introduce errors to slug tests results (Hvorslev, 1951; Butler, 1997). Lastly, estimations of aquifer anisotropy and storage properties
using single well slug test data are unreliable (Fetter, 2001; Beckie and Harvey, 2002; Cardiff et al., 2011).

**Slug Test Analysis**

Analysis of slug test recovery data rely on analytical solutions to mathematical models describing the flow of groundwater to or from the test well (Hvorslev, 1951; Bouwer and Rice, 1976; 1989; Springer and Gelhar, 1991; Hyder et al., 1994; Cooper et al., 1997; Butler, 1997). A variety of models may be used to analyze the slug test recovery data depending on the type of aquifer being investigated (confined/unconfined), the type of slug response observed (overdamped/underdamped), well type (fully-penetrating/partially-penetrating), and the existence of near-well disturbance (skin/no-skin) (Cardiff et al., 2011). Because of the numerous solutions available, it is very seldom that the results from a properly conducted slug test cannot be matched to a solution. However, if a match cannot be obtained, either the conditions do not sufficiently match analytical model assumptions or, more likely, some practical deviation or field error has occurred (Black, 1978). Data that are not amenable for analysis for one method may be usable by changing to another method of analysis (Herzog and Morse, 1990). The mathematical models used in this study include the Bouwer and Rice (1976; Bouwer, 1989), Kansas Geological Survey (KGS) (Hyder et al., 1994), and Springer-Gelhar (Springer and Gelhar, 1991). All of these solutions are suitable for slug test analysis in unconfined aquifers.

**Bouwer and Rice:**

The Bouwer and Rice model is based on the groundwater flow equation for radial flow to a well in an isotropic aquifer:

\[
\frac{\partial^2 h}{\partial r^2} + \frac{1}{r} \frac{\partial h}{\partial r} + K \frac{\partial^2 h}{\partial z^2} = -\frac{S_s}{K} \frac{\partial h}{\partial t}
\]
where storativity is assumed negligible and set to zero (Theim, 1906). The hydraulic conductivity can then be estimated from slug test data according to (Bouwer and Rice, 1976):

\[ K = \frac{r_c^2 \ln \left( \frac{R_e}{r_w} \right)}{2L_e} \frac{1}{t} \ln \left( \frac{H_o}{H_t} \right) \]

where \( R_e \) is the effective radial distance over which \( H_o \) is dissipated, \( r_w \) is the radius of the well screen or to gravel pack, \( L_e \) is the length of the well screen, \( r_c \) is the radius of the casing, \( H_o \) and \( H_t \) are displacements at time zero and \( t \), respectively.

Two key assumptions of the model are (1) the effects of elastic storage mechanisms can be neglected and (2) the position of the water table, and thus the saturated thickness of the formation, does not change during the course of a test. A third and less obvious assumption is that the effective radius \( R_e \) is not a function of slug size. The Bouwer and Rice model is applicable for analysis of over-damped well responses where the early time water level recovery plots linearly on a semi-logarithmic scale. In contrast, underdamped describes oscillatory responses with extremely fast recovery due to inertial effects (Butler, 1997; Spane, 2004) (Figure 4). In an accelerating water column, pressure is not hydrostatic, and the head along the well screen is not equal to the head at the top of the water column.
Figure 4: Types of slug test responses: (1) over-damped, (2) critically damped, (3) under-damped or oscillatory (Spane 2004).

Springer-Gelhar:

The Springer-Gelhar (1991) model extends the Bouwer and Rice method for underdamped responses by applying a momentum balance to the system to account for these inertial affects. The governing equation for the Bouwer and Rice model for continuity in the system inside of the well is expressed as (Bouwer and Rice, 1976):

\[
\frac{dw}{dt} = -\frac{Q}{\pi r_c^2}
\]

where \( Q \) is the discharge rate from the well, \( r_c \) is the inside radius of the well pipe, \( t \) is dimensionless time, and \( w \) is the drawdown of the water level in the well.
By applying a momentum balance to the system, the governing equation for the Springer-Gelhar
model is expressed as (Springer and Gelhar, 1991):

\[ \frac{d^2w^*}{dt^2} + \frac{g}{L_e}w = \frac{g}{L_e}(h_o - h_s) \]

where \( g \) is gravitational acceleration, \( L_e \) is effective well length, and \( (h_o - h_s) \) is the relation
between drawdown at the well screen.

In dimensionless form, this equation can be written as (Springer and Gelhar, 1991):

\[ \frac{d^2w^*}{dt^2} + F \frac{dw^*}{dt} + w^* = 0 \]

where \( t = \sqrt{\frac{g}{L_e}} t \)

where: \( t \) is dimensionless time, \( F \) is the “well factor,” \( w^* \) is dimensionless drawdown, and \( w_o \) is
the initial drawdown.

This is the classical equation for a damped spring and has three solutions: (1) underdamped in
which \( F<2; \) (2) critically damped in which \( F=2; \) (3) overdamped, in which \( F>2. \) By squaring values
of \( w^* \) for the underdamped curves and plotting on a semilogarithmic plot, type curves are obtained
for matching to squared drawdown as a function of dimensionless time. For the overdamped
responses where oscillations are absent, squaring is not necessary for plotting recovery on a
logarithmic scale. The well factor \( F \) is obtained by matching to type curves, and the following
relationships are used to estimate hydraulic conductivity (Springer and Gelhar, 1991):

\[ F = \sqrt{\frac{g}{L_e}} \frac{r_r^2}{2KD} \ln \left( \frac{R_e}{r_w} \right) \]

\[ w^* = \frac{w}{w_o}. \]
KGS (Hyder et al., 1994):

The KGS method, unlike the Bouwer and Rice and Springer Gelhar methods, incorporates transient effects associated with the storage and accounts for skin effects. The KGS model derived by Hyder et al. (1994) is a generalization of the Cooper et al. (1967) method where a semi-analytical solution incorporating the effects of partial penetration, anisotropy, and finite-radius well skins of either higher or lower permeability than the formation. Nine separate transform-space analogs are used to describe a series of constant-head or impermeable upper and lower aquifer boundaries. The KGS method utilizes the groundwater flow equation for transient flow through an anisotropic aquifer (Hyder et al., 1994):

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r} \frac{\partial h}{\partial r} + \frac{K_v}{K_r} \frac{\partial^2 h}{\partial z^2} = -\frac{S_s}{K_r} \frac{\partial h}{\partial t}.$$ 

Normalized head versus the logarithm of $\beta$ for a particular well-formation configuration is used to generate a series of type curves corresponding to a different value of the storage parameter, $\alpha$. The curves and their parameterization are described as (Hyder et al., 1994):

$$\frac{H(t)}{H} = f\left(\beta, \alpha, \varphi, \frac{d}{b'}, \frac{b}{b'}\right)$$

where $H(t)$ is the height of water level displacement at time $t$, $H$ is the initial water level in the well, $f$ are the Fourier-transform variables, $\beta$ is aquifer thickness, $\alpha$ is, $\varphi$ is the square root of the anisotropy ratio over the aspect ratio, and $\frac{d}{b'}, \frac{b}{b'}$ are the upper and lower boundaries of the
configuration. If non-unity skin factors are used, the type curves include $K_r$ and $K_r'$ which describe the hydraulic conductivity of the aquifer skin, respectively. Although the KGS method provides reasonable $K$ estimates, estimation of specific storage obtained from a single well slug-test should not be considered reliable. Instead, multi-well slug tests involving the use of observation wells when performing slug tests can be used to provide more reliable estimates of storativity than a conventional single-well test (Karasaki et al., 1988; Butler, 1997).

In this study, the three numerical models described above are utilized (where appropriate) to determine the best fit to slug test response data (Figure 5). Multiple analysis methods are applied when possible to honor findings from previous studies indicating variability in $K$ estimates from one method to another. Campbell et al. (1990) found that from a number of analysis methods, the Bouwer and Rice provided the most consistent estimates of $K$ and was the least time consuming. Hyder and Butler (1995) determined that the Cooper et al. (1967) model performed better than Bouwer and Rice in homogenous, anisotropic formations or in aquifers with storage parameters greater than $1.0\times10^{-3} \text{ m}^{-1}$. Fabbri et al. (2012) asserts that the KGS method produces the best estimation of $K$ because it accounts for the elastic storage of the aquifer and utilizes the entire recovery data set, whereas Bouwer and Rice is limited to early time data. Multiple analysis methods ensure best fits to the recovery data and encompass underdamped, critically damped and overdamped responses.
Figure 5: Examples of each of the slug test analysis methods used in this study: (1) Springer Gelhar, (2) Bouwer and Rice, and (3) KGS or Hyder et al. 1994.
Current Guidelines for Conducting Slug Tests in the Field - Butler

In his seminal book: “The Design, Performance, and Analysis of Slug Tests”, Butler (1997) addresses many common mistakes associated with slug testing. He primarily attributes the lower estimation of $K$ by slug tests, when compared to aquifer tests, to poor well development and vertical anisotropy, but also suggests more careful data collection in the field can greatly reduce skepticism of slug test derived $K$ values. To reduce field error, Butler has produced guidelines for the design and performance of slug tests (Butler, 1997 and Butler, 2003).

These eight design guidelines from Butler (1997) include:

1. Well-drilling procedures that minimize the generation of drilling debris should be employed whenever possible. Driving based methods, such as a cable-tool, pneumatic/hydraulic hammering, or rotosonic methods are probably best in this regard.

2. Well-development activities should be directed at developing discrete intervals along the well screen. Development procedures that do not stress discrete portions of the well screen may prove rather ineffective, leaving substantial portions of the screened interval virtually untouched by development. Vertical flow within the filter pack can diminish the effectiveness of development efforts; so, some considerations should be given to use of post-installation procedures that may result in more complete development. These include development prior to emplacement of the filter packs that decrease vertical flow, or use of natural filter packs in unstable formations;

3. The possibility of a low-$K$ skin should by a preliminary analysis of the response data using a theoretical model for slug tests in homogeneous formations. A physical implausible specific storage estimate is strong evidence that a skin is affecting the response data;
4. The nominal screen length should be used for the effective screen length parameter in practically all cases;

5. The radius of the filter pack should be used for the effective screen radius parameter in wells with artificial filter packs, while the nominal screen radius may be a better choice for wells with natural filter packs if development has been limited.

6. The nominal radius of the well casing should normally be used for the effective casing radius in conventional slug tests. A comparison of the theoretical and measured values for the initial displacement will indicate the appropriateness of this recommendation for any particular test. The effective casing radius will be a function of the compressibility of water and test equipment in the case of a shut-in slug test;

7. Three or more slug tests should be performed at each well. Two or more different values for the initial displacement (varying by at least a factor of two) should be used in these tests. The first and last tests of the series should employ the same initial displacement, so that the effects of a dynamic skin can be separated from a reproducible dependence on the initial displacement. The direction of flow should also be varied between tests so that a skin-related directional dependence can be identified and, for the case of a well screened across or near the water table, the appropriate manner to represent the water table can be determined. These repeat tests should enable the effectiveness of well-development activities and the viability of conventional slug-test theory to be evaluated at each well;

8. The primary direction of flow during a series of slug test should be from the formation into the well. Slug-induced flow from the well into the formation will often lead to decreases in hydraulic conductivity as a result of mobilized fine material being lodged deeper in the formation (Butler, 1997).
Butler (2003) provides three additional guidelines:

1. *Slug tests should be initiated very rapidly relative to the formation response, so that details of the initiation process can be ignored in the analysis.*

2. *A series of tests should be performed at each well using a range of initial displacements to demonstrate that any dependence on initial displacement can be justifiably neglected in the analysis.*

3. *The pressure transducer in the water column should be placed close to the static water level, so that a type-curve correction for water-column acceleration is not necessary.*

Butler (2020) just recently released the 2nd edition of “The Design, Performance, and Analysis of Slug Tests” which contains five additional guidelines not contained in the first edition:

1. *The equipment used to obtain and store head measurements during a slug test must be appropriate for the expected head response. In formations of moderate-high hydraulic conductivity, a pressure transducer connected to a data-acquisition device is the best option. In less permeable settings, use of an electric tape is also acceptable.*

2. *Head measurements should begin prior to test initiation. The duration of pretest monitoring depends on the expected test length. In moderate-to-high K settings, measurements should begin at least 30 s prior to test initiation; measurements should begin several hours or more prior to initiation in less permeable settings.*

3. *A slug should be initiated near instantaneously relative to the formation response. A near-instantaneous initiation is needed to satisfy assumptions invoked in the more rigorous methods for the analysis of test data. In high-K formations, test initiation using pneumatic*
or packer-based systems is most appropriate. Initiation using a solid slug is reasonable alternative in less permeable media.

4. Measurement of both the expected \((H_o^*)\) and measured \((H_o)\) initial displacements is required. These two quantities should be compared to assess the appropriateness of the nominal casing radius and, in rapidly responding systems, the relative speed of test initiation and the impact of transducer placement.

5. The residual deviation from static should be less than 5% of the initial displacement before a slug test is repeated at a well. If the initial displacement is changed between tests, the recovery criterion should be applied using the value for the second test. If there is uncertainty about whether incomplete recovery is affecting responses, test data should be plotted as the log of the normalized deviation from static versus time. A near-linear plot indicates that the residual deviation is not significantly affecting test responses.

Butler’s guidelines are thorough but are not geared specifically toward performing large-displacement pneumatic slugs. Moreover, guidelines specific to pneumatic slug tests are lacking in the literature.

Knowledge in the field of slug testing is extensive, as outlined in the proceeding literature review. In this study, we aim to add to this knowledge base by performing a series of pneumatic slug tests in three intermediate to high \(K\) aquifers encompassing homogeneous, mildly heterogeneous, and moderate to highly heterogeneous conditions to examine \(K\) dependence on slug size. Slug test estimated \(K\) values at Asylum Lake are compared to \(K\) values derived from a 28-hour aquifer pumping test to examine for method bias. In addition, a series of multi-well pneumatic slug tests
were performed at Asylum Lake in hopes of obtaining (1) a reliable storage parameter (comparable to an aquifer pumping test) and (2) testing the effect of slug size on storage parameters for multi-well slug tests. Lastly, we developed guidelines for performing pneumatic slug testing in the field using our newly designed pneumatic unit which provides a unique opportunity to perform much larger slug tests, as well as a range of smaller tests, for assessing how varying slug sizes affect \( K \) values.

**PROJECT OBJECTIVES**

The major objectives of this study were to investigate \( K \) dependence on slug size as well as develop guidelines for performing large pneumatic slug tests in the field.

These project objectives were addressed through the following research questions:

1. What is the sensitivity and magnitude of slug size on \( K \)?
2. How do \( K \) values from a large pneumatic slug method compare to \( K \) values derived from small displacement physical slug tests and multi-well pumping tests?
3. Are specific storage estimates obtained from multi-well slug tests representative of the aquifer?
4. What guidelines for using large pneumatic slugs should be followed to obtain reliable estimates of hydraulic conductivity in intermediate to high \( K \) aquifers?
METHODS

This study investigated $K$ dependence on slug size and proposed guidelines for performing large pneumatic slug testing in the field. This was accomplished through a combination of both positive and negative (vacuum) displacement pneumatic slug testing on wells located in unconfined aquifers. Once a pneumatic slug testing procedure was formulated, $K$ estimates were obtained from the pneumatic method and compared to $K$ estimates derived from physical slug tests, and in the case of Asylum Lake, aquifer pumping tests. The large pneumatic slug method developed in this study was tested at three field sites comprised of unconfined aquifers with near homogenous, mildly heterogeneous and moderate to highly heterogeneous conditions. The dependency of $K$ on slug size and the ability of multi-well slug tests to produce reasonable storativity values were also evaluated at Asylum Lake.

Study Area

Three well fields were tested in this study, (1) the Muskegon Site, (2) the Asylum Lake Site, and (3) the Grand Rapids Site. The Muskegon site was contaminated by PFAS and consists of a series of shallow, intermediate, and deep wells installed in a downward fining sequence comprised of mostly fine to medium sands overlying fine grained lacustrine sediments (Figure 6). The Asylum Lake well field was situated in an unconfined glacial outwash aquifer of regional extent that is comprised of both well sorted and poorly sorted sands with some gravel and isolated clay lenses.
(Figure 7a). The Grand Rapids well field was located in heterogenous glacier moraine sediments deposited during a catastrophic flood event with a very broad distribution of grain sizes ranging from fine sand to boulders (Figure 8).

Muskegon Well Field:

Figure 6: Muskegon well field locator map (6a) and site map with well locations (6b) created using Google Earth.
The Muskegon well field was located on a brown field re-development site situated along the southwestern edge of Muskegon Lake. The well field consisted of a series of 10 shallow, intermediate, and deep stick-up wells situated in an unconfined aquifer with a mildly heterogeneous downward fining sequence. All wells were installed within a 2.5-week period in Spring 2019 using hollow stem drilling and were developed using low-flow submersible pumps. The static water level in the area was, on average, about 7 ft below ground surface. The intermediate depth wells range from 25 ft - 46 ft below land surface and were of particular interest in this study as they allowed for larger displacements than the shallow wells. A total of 9 out of 10 possible intermediate depth wells were tested; well 7I, located in an old lime storage area, was not suitable for slug testing. Access to the Muskegon Well Field was provided by FTC&H, Inc. environmental consultants.

Asylum Lake Well Field 1:
Figure 7: 7a and 7b show a locator map and site map with well locations of Asylum Lake well field 1 created using Google Earth. 7c shows a detailed diagram of Asylum Lake Well Field 1 (HFC, 2019).

Well field 1 was located approximately 800 ft east of the Asylum Lake Preserve parking lot (S. Drake Rd., north of the WMU Parkview Campus) situated in an unconfined glacial outwash aquifer with varying degrees of sorting. The water table was located approximately 62 ft below ground surface. Groundwater flow in the area was towards the north and follows the local topography, ultimately discharging in Asylum Lake. Well Field 1 contained 14 flush-mount monitoring wells and one pumping well (Figure 7b). Of the 14 monitoring wells, only 6 were viable for pneumatic slug testing as the other 8 wells were either screened across the water table,
larger than 2 inches in diameter, or would not allow the buildup of pressure likely due to cracks in
the casing or poor seals between casing sections.

Grand Rapids Well Field:

Figure 8: Grand Rapids well field locator map (8a) and site map with well locations (8b) created using Google
Earth.
The Grand Rapids well field was situated near the Grand Rapids Gravel pit located approximately 1/3 of a mile northeast of the Grand River. The proximity of the wells to the gravel pit allowed for a unique opportunity to view the cross-sectional composition of the aquifer rather than solely relying on drillers logs (Figure 9). Aquifer sediments consisted of fine to coarse sand, gravel, and boulders. Ripple marks and cross-beding are present in concentrated sand layers. The water table was located approximately 28 ft below ground surface. Groundwater flow in the area is southwest towards the Grand River. The well field contains two nested wells, one deep (76.5 ft) and one shallow (37 ft). Both wells were installed using hollow stem auger a month prior to data collection. Access to the Grand Rapids Well Field was also provided by FTC&H, Inc. environmental consultants.
Figure 9: Images of the Grand Rapids unconfined aquifer taken in the gravel pit adjacent to the well field.

Heterogeneity of the aquifer is clearly seen (9c and 9f). Unconsolidated material ranges in size from fine sand to small boulders between 10 and 20 cm in diameter (9d and 9e).
The Pneumatic Slug Unit

The primary purpose of a pneumatic manifold (Figure 10) is to provide a seal between the inside of the well and atmosphere and to facilitate a near instantaneous pressure release for the start of the slug test (Reeves et al., 2020). The pneumatic slug unit used in this study was designed by Dan Greene and built by Tanten Buszka. The manifold was designed specifically for 2-inch monitoring wells, the standard diameter for monitoring wells in the United States. This design could incorporate an adapter to fit wells of a different diameter. The K-packers are suitable for sealing the well for both vacuum and positive pressure slug tests (Reeves et al., 2020). The unit was used in combination with a vacuum pump and air compressor to pressurize the water column in the well, a pressure transducer and cable to record water level changes, and a field laptop computer for the starting and stopping of tests.
Figure 10: Pneumatic slug unit and transducer.
Pneumatic Slug Field Testing Procedure

The following pneumatic slug test procedure was followed for all data collection in the field:

1. Remove the well cap and allow the water column to equilibrate with atmospheric pressure for 15 minutes.
2. Measure and record initial static water level reading.
3. Attach pneumatic slug unit to the top of the well casing. For flush mounted wells, make sure to leave enough room so that the valve handle can easily open and close.
4. Thread transducer and cable through the top of the pneumatic unit and down to the desired depth in the well. Seal the transducer cable and top of unit with silicon rubber stopper and plastic washer.
5. Set up field laptop and connect transducer. The WinSitu 5 program was used in this study to record all slug test data.
6. Once the transducer is in place, a new test for recording slug displacement can be created. The test should be created before the well is pressurized and not during or after as this can introduce errors into the initial water level reading and future displacement data.
7. Both maximum positive and negative pressure slug displacements for each well should be computed based on static water level, screen length, and well depth. If performing a positive slug test, water level cannot drop below the screened interval. If performing a negative slug test, the water level cannot be pulled into the pneumatic unit at the top of the well or the vacuum pump will sustain damage. When applicable, both positive and negative displacement slug tests should be performed on each well. However, shallow water tables can limit displacements necessary for negative slugs.
8. Begin pressurizing the well for the maximum slug (either positive or negative). Air compressors are used for positive displacement tests, and vacuum pumps are used for negative displacement tests. The desired head change in feet will need to be converted from gauge readings of either psi for positive pressure tests or inches of mercury for negative tests.

9. While pressurizing the well, make sure the shut-in pressure is holding in the well by removing the pressure source and checking that the gauge pressure remains fairly constant. Make sure there are no leaks around that top of the unit or around the well casing.

10. Once the desired shut-in pressure becomes constant, start the data collection on the field computer. Make sure the test is started before the pneumatic unit valve is opened so that all of the early time data is obtained.

11. Open the valve to start the test. Open the valve quickly so the pressure equilibrates instantaneously.

12. Wait five minutes or until the well is fully recovered to end the test.

13. Perform 2 maximum slug tests before scaling down 75%, 50%, 25% of the maximum slug.

14. Repeat the full sequence using negative pressure.

15. Remove the transducer and cable from the top of the pneumatic unit. Remove the unit from the well. Replace the transducer, this time the transducer only needs to be placed at about 5 feet below the water table.

16. Perform a physical slug-out test using a 2-foot displacement slug on the well. Take precaution that the slug is fully submerged.

17. Check the quality of the data prior to moving on to the next well. Redo any tests if needed.
The pneumatic unit, field equipment, and slug testing performed in the field are shown in Figure 11.
Figure 11: Image 11a displays the equipment used in this study for performing pneumatic slug tests in the field. Image 11b illustrates slug testing in stick up wells at the Muskegon site. Image 11c illustrates slug testing in flush mount wells at the Asylum Lake Well Field.
Multi-Well Slug Tests – Asylum Lake Well Field 1

Seven multi-well pneumatic slug tests (four vacuum and three positive) were conducted at wells AL-139 and AL-127 located approximately 10 ft from each other. AL-139 served as the test well with AL-127 functioning as the observation well. Multi-well tests followed the same procedure as single-well slug tests with the exception that two transducers were used (one in each well). Prior to pressurizing the test well, transducer data collection was initiated in the observation well. Post recovery, transducer data in the observation well was stopped. Multi-well slug testing in the field is shown in Figure 12.

Figure 12: Both Image 12a and 12b illustrate the performance of the multi-well slug test in the field. A transducer and the pneumatic slug unit were set in the test well, while only a transducer was set in the observation well. A single field computer was used to generate, start, and stop tests for both transducers.
Aquifer Pumping Test – Asylum Lake Well Field 1

Two aquifer pumping tests were performed over the summer during the Hydrogeology Field Camp (HFC) Modules 1 and 2, 2019. For both tests, the Standard Operating Procedures: Asylum Lake 48 Hour Pump Test Guide written by Jay Kim were adapted for a 28-hour pump test. Values of $K$ and $S$ for all wells located in well field 1 at Asylum Lake were determined from pump test field data. Images of the Module 1 pumping test are shown in Figure 13. The standard operating procedure is included in the Appendix.

![Figure 13: Images showing students from Western Michigan University Summer I Hydrogeology Field Camp performing a 28-hour aquifer pumping test at Asylum Lake. Drawdown data in observation wells was collected manually by the students and using transducers.](image-url)
Well Development – Asylum Lake Well Field 1

Wells at the Asylum Lake well field were installed over a period of almost 30 years using multiple installation methods, as outlined in Table 1, from drillers logs provided by the HFC. Of the 6 wells that were viable for pneumatic slug testing, only 2 provided reasonable $K$ estimates comparable to aquifer pumping test results. The four poorly performing wells had a pronounced skin either due to drilling methods used for installation, fines gathered around the well screens, or perhaps biofilms around the well screens. It was also unknown if any of the monitoring wells were developed immediately after installation. To investigate sources of low $K$, a down hole camera was used. The camera images indicated a need for well re-development.

Table 1 – Wells installed at Asylum Lake

<table>
<thead>
<tr>
<th>Well ID</th>
<th>Installation Date</th>
<th>Driller</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL 127</td>
<td>6/15/1994</td>
<td>Sterns Drilling Co</td>
<td>Hollow Auger to 30', Mud Rotary to end</td>
</tr>
<tr>
<td>AL 128</td>
<td>7/20/1994</td>
<td>Sterns Drilling Co</td>
<td>Mud Rotary</td>
</tr>
<tr>
<td>AL 139</td>
<td>6/7/2003</td>
<td>Sterns Drilling Co</td>
<td>Mud Rotary</td>
</tr>
<tr>
<td>AL 173</td>
<td>7/28/2003</td>
<td>Sterns Drilling Co</td>
<td>Mud Rotary</td>
</tr>
<tr>
<td>AL 184</td>
<td>7/21/2005</td>
<td>Sterns Drilling Co</td>
<td>Mud Rotary</td>
</tr>
<tr>
<td>AL 101</td>
<td>unknown</td>
<td>Sterns Drilling Co</td>
<td>Rotosonic</td>
</tr>
</tbody>
</table>

The four low-$K$ wells were re-developed via pumping and surging methods in an attempt to remove low-$K$ skins and any biofilms. The chemical additive AQUA Clear PFD by Baroid, Inc. was poured down the well and left for a few days to reduce/remove biofilms and flocculate drilling mud. The wells were then pumped and surged again until the water cleared (Figure 14) using bailers and a
submersible pump. This technique greatly improves the confidence in obtaining reliable water-level and water-quality data (Weight, 2008).

Figure 14: Images 14a illustrates well development with a submersible pump. 14b shows water produced by the submerged pump at the beginning of well development - producing brown water. 14c shows water produced after several rounds of pumping and surging with the submersible pump - producing clear water.
**Slug Test Analysis**

Preliminary analysis of the response data at all three well field locations indicated that the effects of well skin could be ignored without introducing error. Therefore, the Bouwer and Rice, Springer-Gelhar, and KGS analysis methods were used assuming the formations are homogenous, i.e., the hydraulic conductivity of the material immediately surrounding the well is the same as the bulk average conductivity of the formation (Butler, 1997). Pre-analysis, data processing in Excel of field measurements involved converting negative water level response data (from negative pressure test) to positive values by multiplying by a factor of -1. Pre-test noise before the air valve was opened was also removed and time shifted so that the response data began at a time equal to zero. This was done by setting time to zero seconds for the largest displacement measurement. For multi-well slug tests, noise for both slug test data and observation data were removed pre-analysis.

Following processing, AQTESOLV was used to analyze the response data gathered in the field. The Bouwer and Rice and the KGS model were used at both the Muskegon and Grand Rapids sites where oscillatory responses in the data were not observed. When using the Bouwer and Rice straight line method, early time data was always used. When using the KGS model, early time data was preferentially weighted and the maximum $K$ value was set to 1 m/s. At Asylum Lake were inertial effects resulting in slightly under-dampened and critically dampened response data was observed, the Springer-Gelhar method was applied for the single-well test data. The KGS and KGS with skin methods were applied to multi-well slug tests at Asylum Lake. The difference being the KGS without skin model assumes flow properties are uniform within both the skin and the formation while the KGS model with skin assumes the flow properties of the skin differ from the formation. During analysis, a multiplier of 50 was used to place additional weight on the
observation well data during type curve matching. The best fit for each slug test was used to estimate $K$.

**Aquifer Pumping Test Analysis**

Aquifer pumping test data was analyzed using first, the Cooper-Jacob model to help initial parameterization, followed by the Neuman and Tartoksky-Neuman models. A quick description of these analysis methods is provided here. The Cooper and Jacob (1946) solution is a late-time approximation to the Theis (1935) method that involves matching a straight line to observed drawdown data to determine transmissivity and storativity. The Neuman (1974) solution is a modification of Boulton (1973) and takes into account the aquifer response known as delayed yield. This is done with a double Theis type curve match. Type curve A represents early time data with elastic storage, and type curve B represents late time data with delayed yield. These two curves are connected by a horizontal transition between the two that is a function of partial penetration and aquifer anisotropy. This method provides estimates for transmissivity, storativity, specific yield, and anisotropy (Neuman 1975). The Tartakovsky-Neuman solution is a modification of Neuman that more reasonably incorporates the unsaturated zone and is considered to provide better estimates of specific yield.

Drawdown data for aquifer pumping tests performed during SI and SII were recorded both manually by students and automatically via transducer for a subset of 12 and 14 wells respectively. Unrealistic dips/fluctuations in recorded water level in the transducer data in some wells occurred from jostling of the transducer cable during manual water level recording by students and were filtered from the data prior to analysis. Transmissivity estimates for all monitoring wells at Asylum
Lake were converted to hydraulic conductivity values using a saturated aquifer thickness of 52 ft based on well logs.
RESULTS

The methods proposed in Chapter 2 were intended to investigate $K$ dependence on slug size and develop pneumatic slug testing guidelines for reliable aquifer parameterization. As discussed above, the development and establishment of a pneumatic procedure and comparison to traditional methods required extensive field work. Both physical and pneumatic slug testing results are provided for all three test sites, and multi-well slug and aquifer pumping tests results at Asylum Lake.

Muskegon Slug Tests

Only positive pneumatic slug tests were performed at the Muskegon well field due to a shallow water table. Slug test recovery data for wells 3I through 10I were analyzed using both the Bouwer and Rice and KGS models. The Springer-Gelhar model was not applied as oscillatory or critically damped responses were not observed in the data. Both the Bouwer and Rice and KGS models produced excellent fits to the data. An example of each analysis method at varying slug sizes for Well 3I is provided in Figure 15.
Although both models produced good fits for the slug test data, the Bouwer and Rice model was chosen to provide a consistent method for analyzing underdamped responses for this site and the Grand Rapids site. A chart of estimated $K$ values for each well and slug sequence is provided in Table 2. A plot of initial displacement versus $K$ for each well and slug sequence is shown in Figure 16. Estimated hydraulic conductivity using the Bouwer and Rice method for the entire well field ranges from $1.1 \times 10^{-4}$ to $3.6 \times 10^{-4}$ ft/s (10 to 31 ft/d). Estimated $K$ values using the KGS model range from $1.0 \times 10^{-4}$ to $3.9 \times 10^{-4}$ ft/s (9 to 34 ft/d).
Table 2 – Muskegon slug test results

<table>
<thead>
<tr>
<th>Well ID</th>
<th>Test ID</th>
<th>Ho (ft)</th>
<th>Bouwer-Rice K (ft/s)</th>
<th>KGS K (ft/s)</th>
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<tr>
<td>MW-31</td>
<td>pMax-1</td>
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<td>3.5×10⁻⁴</td>
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<td></td>
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<td>p75</td>
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<td>3.4×10⁻⁴</td>
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<td></td>
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<td></td>
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<td>2.2×10⁻⁴</td>
<td>2.3×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>p50</td>
<td>13.1</td>
<td>2.2×10⁻⁴</td>
<td>2.6×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>Phys-out</td>
<td>3.0</td>
<td>2.5×10⁻⁴</td>
<td>3.9×10⁻⁴</td>
</tr>
<tr>
<td>MW-81</td>
<td>pMax-1</td>
<td>15.8</td>
<td>1.1×10⁻⁴</td>
<td>1.1×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>pMax-2</td>
<td>22.4</td>
<td>1.1×10⁻⁴</td>
<td>1.0×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>p75</td>
<td>18.5</td>
<td>1.2×10⁻⁴</td>
<td>1.1×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>p50</td>
<td>11.3</td>
<td>1.1×10⁻⁴</td>
<td>1.1×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>Phys-out</td>
<td>4.2</td>
<td>1.1×10⁻⁴</td>
<td>1.7×10⁻⁴</td>
</tr>
<tr>
<td>MW-91</td>
<td>pMax-1</td>
<td>19.5</td>
<td>1.4×10⁻⁴</td>
<td>1.5×10⁻⁴</td>
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<tr>
<td></td>
<td>pMax-2</td>
<td>19.4</td>
<td>1.4×10⁻⁴</td>
<td>1.5×10⁻⁴</td>
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<tr>
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<td>p75</td>
<td>21.1</td>
<td>1.6×10⁻⁴</td>
<td>1.5×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>p50</td>
<td>14.8</td>
<td>1.7×10⁻⁴</td>
<td>1.4×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>Phys-out</td>
<td>1.4</td>
<td>1.6×10⁻⁴</td>
<td>1.6×10⁻⁴</td>
</tr>
<tr>
<td>MW-101</td>
<td>pMax-1</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td></td>
<td>pMax-2</td>
<td>20.1</td>
<td>1.8×10⁻⁴</td>
<td>1.9×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>p75</td>
<td>17.6</td>
<td>2.4×10⁻⁴</td>
<td>2.1×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>p50</td>
<td>13.6</td>
<td>2.5×10⁻⁴</td>
<td>2.3×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>Phys-out</td>
<td>3.6</td>
<td>2.3×10⁻⁴</td>
<td>3.8×10⁻⁴</td>
</tr>
</tbody>
</table>

*nd = no data
Figure 16: Estimated $K$ values sorted by initial displacement for each well at the Muskegon site. No trend between slug size and estimated $K$ is observed for wells 3I, 5I, 6I, 8I, 9I, and 10I. Well 4I shows a slight increase in $K$ with decreasing slug size. All estimated $K$ values are within an order of magnitude.

Asylum Lake Slug Tests

Single-Well Slug Tests:

Of the 6 wells viable for slug testing at the Asylum Lake well field, only 2 wells (AL-101 and AL-182) provided responses indicating a lack of well skin even after well re-development. These two wells were drilled using hollow stem auger and mud rotary methods, respectively. The hollow stem auger method used to install well 101 minimized the formation of any skin effects, unlike the rest of the wells at the site. A water table of approximately 62 ft below land surface allowed for
both positive pressure and vacuum slug tests to be performed at each well. At wells AL-101 and AL-182, a very slight oscillatory response was seen in the data for negative pressure slug tests only. This is likely attributed to the high $K$ value combined with inertia along the water column. Of the three analysis methods, the Springer-Gelhar method provided the best fit for negative pressure slug tests responses. For positive pressure slug tests, the Springer-Gelhar method also provided the best fit for curved early time data, indicating critical dampening. An example of all three analysis methods applied at well AL-101 is shown in Figure 17.

Figure 17: Examples of the Bouwer and Rice (top row), KGS (middle row), and Springer-Gelhar (bottom row) solutions for varying vacuum slug sizes at Well 101 (Asylum Lake Site).
Table 3 – Asylum Lake single-well slug test results

<table>
<thead>
<tr>
<th>Well ID</th>
<th>Best-fit Method</th>
<th>Test ID</th>
<th>Ho (ft)</th>
<th>K (ft/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL-101</td>
<td>Springer-Gelhar</td>
<td>nMax-1</td>
<td>9.7</td>
<td>8.9×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>Springer-Gelhar</td>
<td>nMax-2</td>
<td>9.7</td>
<td>9.3×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>Springer-Gelhar</td>
<td>n75</td>
<td>6.3</td>
<td>1.0×10⁻³</td>
</tr>
<tr>
<td></td>
<td>Springer-Gelhar</td>
<td>n50</td>
<td>4.5</td>
<td>1.2×10⁻³</td>
</tr>
<tr>
<td></td>
<td>Springer-Gelhar</td>
<td>n25</td>
<td>3.0</td>
<td>1.4×10⁻³</td>
</tr>
<tr>
<td>AL-182</td>
<td>Springer-Gelhar</td>
<td>nMax-1</td>
<td>9.5</td>
<td>1.3×10⁻³</td>
</tr>
<tr>
<td></td>
<td>Springer-Gelhar</td>
<td>nMax-2</td>
<td>9.3</td>
<td>1.4×10⁻³</td>
</tr>
<tr>
<td></td>
<td>Springer-Gelhar</td>
<td>n75</td>
<td>6.1</td>
<td>1.6×10⁻³</td>
</tr>
<tr>
<td></td>
<td>Springer-Gelhar</td>
<td>n50</td>
<td>4.6</td>
<td>1.7×10⁻³</td>
</tr>
<tr>
<td></td>
<td>Springer-Gelhar</td>
<td>n25</td>
<td>2.0</td>
<td>1.8×10⁻³</td>
</tr>
</tbody>
</table>

A chart of estimated $K$ values from the best-fit method for each well and slug sequence is provided in Table 3 and illustrated in Figure 18. The $K$ estimates provided in Table 3 allow for an assessment of the reliability of varying slug sizes when compared to aquifer test $K$ estimates for wells AL-101 and Al-182. Using the Springer-Gelhar method, estimated $K$ values at well AL-101 range from $5.7×10⁻⁴$ to $7.9×10⁻⁴$ ft/s ($49$ to $68$ ft/d) for positive pressure slug tests and $9.2×10⁻⁴$ to $1.4×10⁻³$ ft/s ($80$ to $121$ ft/d) for negative pressure slug tests. Estimated values at well AL-182 range from $9.7×10⁻⁴$ to $1.2×10⁻³$ ft/s ($84$ to $104$ ft/d) for positive pressure slug tests and $1.3×10⁻³$ to $1.8×10⁻³$ ft/s ($112$ to $156$ ft/d) for vacuum slug tests. Data from both wells indicated increases in estimated $K$ with decreases in slug size.
Figure 18: Estimated $K$ values sorted by initial displacement for wells Al-182 and Al-101 at the Asylum Lake site. Both wells show slight increases in $K$ with decreasing slug size. All estimated $K$ values are within an order of magnitude.

Multi-well Slug Tests:

For all seven multi-well slug tests performed on AL-139, a clear signal in the observation well AL-127 was observed. This includes three positive and four vacuum pneumatic slug tests. The four vacuum tests yielded the clearest data. The start of the positive pressure slug tests were not as clearly identifiable in the observation data, and therefore, positive pressure tests were not analyzed. Figure 20 shows observation well (AL-127) response data for all four vacuum tests. The deviation from static water level in the observation well was on the order of one-hundredth of a foot, and ranges from approximately -0.02 to -0.05 ft for initial slug displacements between 8 and 25 ft. These perturbations were small, but clearly observed in the data collected in the observation well located 10 ft away from the test well.
Figure 19: Observation Well Response data at well AL-127 for vacuum pneumatic slug tests performed in well AL-139. Recovery data shown in blue and moving average shown in red.

AQTESOLV was used to apply both the KGS and KGS with skin models to recovery data for both wells using the multi-well analysis function. During analysis, a multiplier of 50 was used to place additional weight on the observation well data during type curve matching to account for the analysis methods tendency to favor test well data over observation well data. This provided excellent fits to the test well response data for all four vacuum tests. However, good fits to the observation well data were only obtained for two of the four tests. An example of the best-fit test
is shown in Figure 20. A greater skin around the observation well, as confirmed during single well slug testing to test the effectiveness of the well development, is believed to have had some effect on the results of the other two tests. Estimates of $K$ and $S_s$ for the multi-well vacuum tests using the best-fit method are provided in Table 4 and illustrated in Figures 21 and 22. No significant trend between $K$ and slug size is observed in the data. Estimated $K$ values range from $1.0 \times 10^{-4}$ to $2.2 \times 10^{-4}$ ft/s (9 to 19 ft/d). Even using an analysis method that accounted for skin, these $K$ values are approximately an order of magnitude lower than $K$ estimates from the aquifer pumping test. This was anticipated as both wells were drilled using mud rotary and have a pronounced skin effect.

![Figure 20](image)

**Figure 20**: Analysis example for multi-well test 3 using the KGS with skin method for multi-well slug tests in AQTESOLV.
### Table 4 – Asylum Lake multi-well slug test results

<table>
<thead>
<tr>
<th>Well ID</th>
<th>Best-fit Method</th>
<th>Test ID</th>
<th>$H_0$</th>
<th>$K$</th>
<th>$S_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Well - AL139</td>
<td>KGS w/skin</td>
<td>1</td>
<td>23.0</td>
<td>1.4×10^{-4}</td>
<td>2.8×10^{-3}</td>
</tr>
<tr>
<td>Observation Well - 127</td>
<td>KGS w/skin</td>
<td>2</td>
<td>25.3</td>
<td>1.0×10^{-4}</td>
<td>3.6×10^{-3}</td>
</tr>
<tr>
<td></td>
<td>KGS w/skin</td>
<td>3</td>
<td>12.8</td>
<td>2.2×10^{-4}</td>
<td>2.2×10^{-3}</td>
</tr>
<tr>
<td></td>
<td>KGS w/skin</td>
<td>4</td>
<td>8.0</td>
<td>1.7×10^{-4}</td>
<td>2.5×10^{-3}</td>
</tr>
</tbody>
</table>

### Multi-Well Slug Test Analysis - Estimated $K$

![Graph of estimated $K$ values](image)

Figure 21: Estimated $K$ values sorted by initial displacement for multi-well slug tests conducted at well AL-139 at Asylum Lake.
Values of $S_s$ range from $1.1 \times 10^{-3}$ to $2.9 \times 10^{-3}$ $\text{ft}^{-1}$, and are within the expected range for sandy/gravel aquifers (Domenico and Mifflin, 1965). Figure 22 shows $S_s$ estimates based on initial displacement in the testing well. Opposite of the observed $K$ trends observed in individual slug tests, values of $S_s$ obtained from the multi-well slug tests increase with increasing slug size.

**Asylum Lake – Aquifer Pumping Tests**

Aquifer pumping and recovery data collected using a combination of manual and water level loggers were analyzed separately. The Thesis Residual Drawdown/Recovery method for confined aquifers and the Cooper-Jacob method with the Agarwal solution were used to analyze recovery data. The 28-hour aquifer pumping test performed during SII was selected for comparison with
pneumatic slug test results due to higher data quality as more wells were monitored using water level loggers.

Aquifer pumping test estimates of $K$ for 12 of the 14 monitoring wells at Asylum Lake exhibited classical delayed yield drawdown responses and were analyzed using a hybrid method that first utilizes Cooper-Jacob to constrain $T$ and $S$ values for late and early times and preconditions the Neuman solution for full parameter estimation. The Tartoksky-Neuman solution was then run from the best-fit Neuman solution for potential improvement in values of $S_y$. For 10 of the 12 wells analyzed, the best fit model was the Neuman method. For the remaining two wells, which are close to the pumping well and yielded non-classical drawdown trends, the Cooper-Jacob solution was used for parameter estimation. Best-fit pumping test results are shown in Table 5. Estimated $K$ values for the well field range from $2.2 \times 10^{-3}$ to $3.6 \times 10^{-3}$ ft/s ($190 – 311$ ft/d). Figure 23 compares pneumatic and physical slug test results with aquifer pumping test results at wells AL-101 and AL-182. Pneumatic and physical slug test results at AL-182 are in agreement with aquifer pumping test results, while pneumatic and physical slug test results at AL-101 are slightly lower, but still acceptably within an order of magnitude of aquifer pumping test results. Aquifer pumping test estimates for specific storage range from $1.2 \times 10^{-2}$ to $5.7 \times 10^{-4}$, well within the expected range for sandy/gravel aquifers (Domenico and Mifflin, 1965).
Table 5 – Aquifer pumping test results

<table>
<thead>
<tr>
<th>Well</th>
<th>Best-fit Method</th>
<th>T (ft/s)</th>
<th>K (ft/s)</th>
<th>S</th>
<th>Ss (ft-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>Neuman</td>
<td>0.126</td>
<td>2.4×10⁻³</td>
<td>0.046</td>
<td>8.9×10⁻⁴</td>
</tr>
<tr>
<td>118</td>
<td>Neuman</td>
<td>0.1166</td>
<td>2.2×10⁻³</td>
<td>0.063</td>
<td>1.2×10⁻³</td>
</tr>
<tr>
<td>127</td>
<td>Neuman</td>
<td>0.1233</td>
<td>2.4×10⁻³</td>
<td>0.036</td>
<td>6.9×10⁻⁴</td>
</tr>
<tr>
<td>128</td>
<td>Neuman</td>
<td>0.1342</td>
<td>2.6×10⁻³</td>
<td>0.030</td>
<td>5.7×10⁻⁴</td>
</tr>
<tr>
<td>139</td>
<td>Neuman</td>
<td>0.126</td>
<td>2.4×10⁻³</td>
<td>0.039</td>
<td>7.4×10⁻⁴</td>
</tr>
<tr>
<td>145</td>
<td>Neuman</td>
<td>0.1124</td>
<td>2.2×10⁻³</td>
<td>0.040</td>
<td>7.7×10⁻⁴</td>
</tr>
<tr>
<td>169</td>
<td>Cooper-Jacob</td>
<td>0.139</td>
<td>2.7×10⁻³</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>175</td>
<td>Neuman</td>
<td>0.1216</td>
<td>2.3×10⁻³</td>
<td>0.061</td>
<td>1.2×10⁻³</td>
</tr>
<tr>
<td>178</td>
<td>Cooper-Jacob</td>
<td>0.1885</td>
<td>3.6×10⁻³</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>182</td>
<td>Neuman</td>
<td>0.1277</td>
<td>2.5×10⁻³</td>
<td>0.043</td>
<td>8.2×10⁻⁴</td>
</tr>
<tr>
<td>184</td>
<td>Neuman</td>
<td>0.1147</td>
<td>2.2×10⁻³</td>
<td>0.051</td>
<td>9.8×10⁻⁴</td>
</tr>
<tr>
<td>164</td>
<td>Neuman</td>
<td>0.1242</td>
<td>2.4×10⁻³</td>
<td>0.006</td>
<td>1.2×10⁻⁴</td>
</tr>
</tbody>
</table>

Figure 23: Comparison of pneumatic and physical slug tests to pumping tests for wells AL-101 and AL-182 at Asylum Lake using the method of best-fit.
Distance drawdown data for the SII pumping test shown in Table 6, where also used to determine $T$ and $K$ estimates for the Asylum Lake aquifer. Results are shown in Figure 24. An effective radius for the aquifer pumping test of 679 ft was also estimated.

Table 6 – Distance drawdown data

<table>
<thead>
<tr>
<th>Well ID</th>
<th>Distance From Well</th>
<th>SWL Pre-Pumping</th>
<th>SWL Pre-Pump Shut-off</th>
<th>Max Drawdown</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(ft)</td>
<td>(ft)</td>
<td>(ft)</td>
<td>(ft)</td>
</tr>
<tr>
<td>178</td>
<td>11.6</td>
<td>61.39</td>
<td>62.19</td>
<td>0.80</td>
</tr>
<tr>
<td>101</td>
<td>32.5</td>
<td>60.45</td>
<td>61.13</td>
<td>0.68</td>
</tr>
<tr>
<td>118</td>
<td>38.7</td>
<td>60.81</td>
<td>61.44</td>
<td>0.63</td>
</tr>
<tr>
<td>128</td>
<td>64.2</td>
<td>58.78</td>
<td>59.28</td>
<td>0.50</td>
</tr>
<tr>
<td>145</td>
<td>32.5</td>
<td>59.68</td>
<td>60.28</td>
<td>0.60</td>
</tr>
<tr>
<td>173</td>
<td>37.8</td>
<td>62.23</td>
<td>62.95</td>
<td>0.72</td>
</tr>
<tr>
<td>175</td>
<td>95.6</td>
<td>57.77</td>
<td>58.16</td>
<td>0.39</td>
</tr>
<tr>
<td>176</td>
<td>69.1</td>
<td>62.39</td>
<td>62.85</td>
<td>0.46</td>
</tr>
<tr>
<td>182</td>
<td>78.4</td>
<td>59.8</td>
<td>60.27</td>
<td>0.47</td>
</tr>
<tr>
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<td>60.82</td>
<td>61.27</td>
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<td>127</td>
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<td>61.73</td>
<td>62.13</td>
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<td>61.72</td>
<td>0.42</td>
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<td>9.1</td>
<td>60.47</td>
<td>61.71</td>
<td>1.24</td>
</tr>
<tr>
<td>169</td>
<td>18.7</td>
<td>60.2</td>
<td>61.19</td>
<td>0.99</td>
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</tbody>
</table>
Figure 24: Graph showing distance drawdown results with estimated $T$ and $K$ values for the SII pumping test at Asylum Lake.

**Grand Rapids Slug Tests**

Two wells were tested at the Grand Rapids Well Field: 4s and 4d. Vacuum pneumatic slug tests were performed in Well 4s due to a short water column that precluded positive pressure tests, while both positive pressure and vacuum pneumatic slug tests were performed in well 4d, the deeper of the two wells. The greater depth allowed for positive pressure tests with greater displacements than was physically achievable with vacuum tests. Slug tests for both wells yielded overdamped trends and were analyzed using the Bouwer and Rice and KGS models. An example of the KGS and Bouwer and Rice models applied at well 4s is shown in Figure 25. The KGS method did not provide good fits for either well 4d or well 4s even with parameter adjustments during analysis. A chart of estimated $K$ values from the best-fit method for each well and slug sequence is provided in Table 7 and illustrated in Figures 26 and 27.
Figure 25: Analysis examples of the KGS (top row) and Bouwer and Rice (bottom row) methods for varying slug sizes at Well 4s (Grand Rapids Site).

Table 7 – Grand Rapids slug test results

<table>
<thead>
<tr>
<th>Well ID</th>
<th>Best-fit Method</th>
<th>Test ID</th>
<th>Ho</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(ft)</td>
<td>(ft/s)</td>
</tr>
<tr>
<td>4d</td>
<td>Bouwer-Rice</td>
<td>nMax-1</td>
<td>12.8</td>
<td>6.0×10⁻⁵</td>
</tr>
<tr>
<td></td>
<td>Bouwer-Rice</td>
<td>nMax-2</td>
<td>17.1</td>
<td>4.6×10⁻⁵</td>
</tr>
<tr>
<td></td>
<td>Bouwer-Rice</td>
<td>n75</td>
<td>13.2</td>
<td>5.0×10⁻⁵</td>
</tr>
<tr>
<td></td>
<td>Bouwer-Rice</td>
<td>n50</td>
<td>7.1</td>
<td>9.4×10⁻⁵</td>
</tr>
<tr>
<td></td>
<td>Bouwer-Rice</td>
<td>n25</td>
<td>3.3</td>
<td>2.2×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>Bouwer-Rice</td>
<td>nPhys-1</td>
<td>1.1</td>
<td>6.6×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>Bouwer-Rice</td>
<td>p22-1</td>
<td>16.3</td>
<td>4.6×10⁻⁵</td>
</tr>
<tr>
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<td>Bouwer-Rice</td>
<td>p22-3</td>
<td>17.5</td>
<td>2.1×10⁻⁵</td>
</tr>
<tr>
<td></td>
<td>Bouwer-Rice</td>
<td>p33</td>
<td>29.6</td>
<td>1.6×10⁻⁵</td>
</tr>
<tr>
<td></td>
<td>Bouwer-Rice</td>
<td>p45</td>
<td>38.4</td>
<td>6.4×10⁻⁶</td>
</tr>
<tr>
<td>4s</td>
<td>Bouwer-Rice</td>
<td>nMax-1</td>
<td>-14.2</td>
<td>1.9×10⁻³</td>
</tr>
<tr>
<td></td>
<td>Bouwer-Rice</td>
<td>nMax-2</td>
<td>-14.7</td>
<td>1.9×10⁻³</td>
</tr>
<tr>
<td></td>
<td>Bouwer-Rice</td>
<td>n75</td>
<td>-12.5</td>
<td>2.0×10⁻³</td>
</tr>
<tr>
<td></td>
<td>Bouwer-Rice</td>
<td>n50</td>
<td>-10.0</td>
<td>2.2×10⁻³</td>
</tr>
<tr>
<td></td>
<td>Bouwer-Rice</td>
<td>n25</td>
<td>-6.0</td>
<td>2.2×10⁻³</td>
</tr>
<tr>
<td></td>
<td>Bouwer-Rice</td>
<td>nPhys-1</td>
<td>-4.1</td>
<td>2.5×10⁻³</td>
</tr>
<tr>
<td></td>
<td>Bouwer-Rice</td>
<td>nPhys-2</td>
<td>-3.6</td>
<td>2.9×10⁻³</td>
</tr>
</tbody>
</table>
Estimated $K$ values for vacuum tests at well 4d range from $4.6 \times 10^{-5}$ to $6.6 \times 10^{-4}$ ft/s (4 to 57 ft/d).

Estimated $K$ values for positive pressure tests range from $6.4 \times 10^{-6}$ to $4.6 \times 10^{-5}$ ft/s (0.6 to 4 ft/d).

Estimated $K$ values for vacuum tests in well 4s range from $2.0 \times 10^{-3}$ to $2.6 \times 10^{-3}$ ft/s (173 to 225 ft/d).

Figure 26: Estimated $K$ values sorted by initial displacement and test type for well 4d at the Grand Rapids site. $K$ estimates increase with decreasing slug size. Estimated $K$ values encompass three orders of magnitude.
On average, positive pressure tests performed on well 4d were an order of magnitude lower. This was attributed to higher initial displacements rather than any directional effects. For both vacuum and positive pressure tests, estimated $K$ values for well 4d, significantly decrease with increasing slug size. This trend spans nearly three orders of magnitude. Only a slight decrease in estimated $K$ was observed with increasing slug size at well 4s.

Figure 27: Estimated $K$ values sorted by initial displacement for well 4s at the Grand Rapids site. No trend between slug size and estimated $K$ is observed.
DISCUSSION AND CONCLUSION

The major objectives of this study were to investigate $K$ dependence on slug size and develop guidelines for performing pneumatic slug tests in the field. To examine the relationship between hydraulic conductivity and slug size, a series of slug tests with a range of initial displacements were performed at each site. First, the maximum-sized pneumatic slug was performed in each well twice to minimize the potential for well development during the series of slug tests. This was followed by a series of tests with displacements of 75%, 50%, and 25% the maximum displacement. Lastly, a smaller 2 ft displacement physical slug test or a similarly-sized pneumatic slug test was conducted in each well. The results of slug tests at each study site are discussed below.

Hydraulic Conductivity and Slug Size

The Muskegon aquifer had the lowest hydraulic conductivity of all three sites tested in this study. It was also the most homogenous in terms of aquifer grain size and grain size distribution. Of the 7 wells viable for slug testing at the Muskegon Well Field, two wells showed a slightly negative correlation between estimated $K$ and increasing slug size and five wells showed no effects on estimated $K$ with increasing slug size. Therefore, it was concluded there is a lack of scale effect at the Muskegon site. This is consistent with Makuch et al. (1999), who found no variations of $K$ with scale in homogenous media, but did for more heterogenous media.
Aquifer tests conducted at Asylum Lake involved single-well and multi-well pneumatic slugs, physical slugs, and pumping tests. Both wells used for single-well slug testing exhibited a slight negative correlation between estimated $K$ and increasing slug size that was less than half an order of magnitude. The decreases in $K$ were over a relatively small range and it was unclear if this was caused by a scale effect or by turbulent energy loss in the porous media surrounding the well screen.

For the series of multi-well tests, no clear relationship between estimated $K$ and increasing slug size was observed. Slug test estimated $K$ for single well pneumatic slug tests were in good agreement with pumping tests, while multi-well $K$ estimates were an order of magnitude smaller than aquifer test results due to skin effects. Good agreement between $K$ estimates produced by slug tests and aquifer tests in high $K$ aquifers, specifically glacial outwash aquifers similar to that tested at Asylum Lake, has been previously acknowledged by Rovey and Cherkauer (1995). Good agreement between the slug test estimated $K$ and aquifer test estimated $K$ at Asylum Lake serves as a validation of the pneumatic slug unit and developed procedure used for conducting slug tests. Furthermore, the general agreement in $K$ values suggests that no method bias exits.

Of the three aquifers that were slug tested, the Grand Rapids site was the most heterogeneous in terms of grain size and grain size distribution. The Grand Rapids well field was chosen specifically for this reason in hopes that a more heterogeneous aquifer would show a decisive scale effect between $K$ and slug size. It was hypothesized that a scale effect would be observed similar to that seen in studies reported by Rovey (1997), Makuch and Cherkauer (1998), and Makuch et al.
(1999), where a scale effect showed increases in estimated $K$ with increasing volume of the aquifer tested. As shown in Figure 26, a scale effect at Grand Rapids was observed, but the relationship between $K$ and increasing slug size was the opposite of that found in these previous studies (Rovey, 1997; Makuch and Cherkauer, 1998; and Makuch et al., 1999. At Grand Rapids, estimated $K$ values dramatically decreased with increasing slug size around three orders of magnitude; with the lowest $K$ estimates produced from positive pressure tests. This was attributed to positive pressure tests allowing for larger initial displacements and subsequently greater turbulent energy loss, rather than a directional flow component reported by Ismael (2016).

Conclusions:

If significant increases in $K$ occur with increasing scale of measurement, in this case increasing slug size, like that reported in previous studies, then the estimated hydraulic conductivity value from a test should increase with slug size in heterogeneous material. Based on the results from the Muskegon, Asylum Lake, and Grand Rapids sites, it cannot be concluded decisively that a scale effect between $K$ and slug size exists. Several explanations could be responsible for the increases in estimated $K$ with decreasing slug size observed at Grand Rapids, and to a lesser degree, at Asylum Lake. These findings conflict with previous studies by Rovey (1997), and Makuch and Cherkauer (1998), Makuch et al. (1999) that show a pronounced scale effect based on pumping tests. Possible explanations are provided below.

1. A positive skin exists around the wells tested at Asylum Lake and Grand Rapids that only smaller slugs are reflecting.
• This is not likely the case as negative skins not positive skins are typically created during well installation for all drilling methods. Moreover, no skin effect was detected for the two single-well tests at Asylum Lake, the nine wells tested at the Muskegon site, or the two wells at the Grand Rapids site.

2. The slug test is being developed during the series of slug tests which mobilizes fines and increases estimated $K$ values in later tests.

• Well development should enhance the hydrologic connection with the well to the aquifer which would provide more reliable and representative values of $K$ regardless of slug size. Initializing the slug test sequence with two maximum sized slugs should minimize further well development when testing smaller sized slugs. This trend is not observed for the Muskegon well 4d where the slug sequence began with maximum vacuum slugs through small vacuum slugs, and were then followed by positive pressure slugs of smaller to maximum size.

3. Increased turbulent energy loss is occurring with increasing slug sizes as a result of increased flow velocities into or out of the well. Smaller sized slugs in intermediate to high-$K$ aquifers generate lower flow velocities and less turbulent energy loss, resulting in higher $K$ values.

• This is the most likely scenario. Well hydraulics describes radially convergent flow to a well. Increased frictional losses and non-uniform flow back into and/or out of the well are known to occur at higher velocities (Cooley and Cunningham, 1979).

• Water movement in the aquifer tends to follow a path that minimizes total energy loss, defined as the sum of all energy losses in the well and in the aquifer
medium. For aquifers of relatively low $K$, flow paths into/out of the well tend to be more nearly radial than for cases involving aquifers of relatively high $K$ (Cooley and Cunningham, 1979).

- This assertion is not proven and requires additional research to confirm.

Increasing $K$ estimates with decreasing scale of measurement (slug size) observed at the Grand Rapid site and to a lesser extent Asylum Lake, are likely related to explanations #2 and/or #3 discussed above; with explanation #3 being the more probable explanation.

Maximum pneumatic slug size is limited by either: (1) the distance from the top of the well above the top of the water column for negative displacement slugs, or (2) the distance from the top of the water column down to the top of the well screen for positive displacement wells. To avoid underestimation of $K$ values, like that seen at the Grand Rapids site, an upper limit boundary to the size of pneumatic slugs performed in intermediate to high $K$ aquifers should be considered. Currently, the upper limit for a negative displacement slug is considered equivalent to the vacuum pressure at which water boils and transitions to the air phase. This occurs at approximately 32.8 ft at 20°C according to the ideal gas law, with maximum slugs closer to 27.9 ft in practice. The upper limit of a positive displacement slug is less restricted and depends on the pressures that the well packers of the pneumatic slug testing unit can accommodate. The largest positive displacement slug in this study approached 40 ft. Based on results from our three field sites, it is estimated/recommended that an upper initial displacement limit of around 8 ft to 10 ft for slug sizes is appropriate to adequately sample the aquifer, but not result in too much turbulent energy loss. An upper limit should be used when conducting pneumatic slug tests in high $K$ aquifers.
Specific Storage and Slug Size

Traditionally, slug tests have been performed using a single well as both the site of aquifer perturbations and recovery. This practice maintains the common perception that a slug test only affects a small volume of the aquifer immediately adjacent the well screen (Butler, 2020). However, the aquifer responses collected in the observation well during the multi-well slug testing at Asylum Lake clearly demonstrate that slug perturbations extend to a greater volume of the aquifer than assumed. For example, analysis using the Bouwer and Rice method on AL139, yields an effective radius of only 4.1 ft, yet the perturbation reaches the monitoring well located 10 ft away. Moreover, the effective radius predicted by Bouwer and Rice does not take slug size into account, which appears counter intuitive as larger slugs should naturally lead to larger perturbations in the aquifer.

The volume of aquifer affected is most dependent on the dimensionless storage parameter $\alpha$, where smaller values of $\alpha$ represent greater volumes of the aquifer affected (Barker and Black, 1983; Sageev, 1986; Karasaki et al., 1988; Butler, 2020). For this reason, multi-well slug tests provide more reliable estimate of $S_s$ than can be obtained from single-well tests. Multi-well slug test estimated $S_s$ values range from $1.1 \times 10^{-3}$ to $2.9 \times 10^{-3}$ ft$^{-1}$ at Asylum Lake and are within the range of pumping test estimates for specific storage ($1.2 \times 10^{-4}$ to $1.2 \times 10^{-3}$ ft$^{-1}$) attained at Asylum Lake, and representative of sandy/gravel aquifers (Domenico and Mifflin, 1965). Single-well $S_s$ estimates at the two wells are $2.9 \times 10^{-12}$ ft$^{-1}$ at well AL-101 and $5.1 \times 10^{-12}$ ft$^{-1}$ at well AL-182. These unrealistically low $S_s$ values often indicate the presence of well skin, however, the analyses clearly demonstrate that there is negligible skin. These results indicate that in high $K$ aquifers,
multi-well tests can produce reliable $S_r$ estimates representative of the aquifer. Though it should be stated that $S_r$ can only be estimated from slug tests using either the Cooper or the KGS methods, neither of these solutions appear to provide reliable estimates.

Guidelines for Performing Pneumatic Slug Tests in the Field

Extensive work on slug testing in the field has resulted in numerous guidelines for their performance in the field (Butler 1997; 2003; 2020). However, these guidelines have focused mostly on small-displacement physical slug tests. In this study, we add to this body of work by suggesting guidelines specifically for the performance of larger displacement pneumatic slug tests in the field. Our suggestions, based on over 100 pneumatic slug tests performed throughout the course of this study, are discussed below:

1. Estimated $K$ values from older or poorly developed wells, even when well-development methods are applied, should be used with caution. Comparisons of $K$ values collected pre and post-well development at Asylum Lake showed no improvement, and remained an order of magnitude lower than estimates produced by the two wells with negligible skin effects and aquifer pumping test results.

2. In homogenous aquifers, if head recovery is time-consuming for larger displacement tests, smaller initial displacement tests can be performed to save time as in homogeneous aquifers, like Muskegon, slug size does not affect estimated $K$ values.
3. In the case of lower $K$ aquifers with longer recovery times, the transducer can also be left in the well to record head recovery free from the computer so that other tests can be conducted. This does not affect data collection.

4. To avoid artificially underestimated $K$ values caused by turbulent energy loss, an upper limit of around 8-10 ft for slug sizes should be considered when performing pneumatic slugs in high $K$ aquifers.

5. Pneumatic slug tests should be used over smaller physical slugs whenever possible in the field as they provide for a range of initial displacements suitable for both low and high $K$ aquifers, closely approximate the instantaneous head change assumption used in all slug test analysis methods, and generally produce cleaner data than physical slug tests.

6. When conducting slug tests in high $K$ aquifers it is better to use a transducer with fast linear data collection every ½ or ¼ of a second to capture critically damped and underdamped effects with very fast transience. Data collection on the transducer should be started approximately 3-5 seconds prior to slug test initiation to accurately capture the full trend of head recovery regardless of slug size. If the transducer has the correct range, it can be placed near the bottom of the well without affecting data collection. This is critical for larger displacement tests.

7. To compute correct initial displacement, record both the transducer water level for initial displacement and the gauge pressure reading on the pneumatic unit. If the two readings are not in agreement, for intermediate $K$ and high $K$ aquifers, use the recorded transducer displacement data over the gauge reading to insure best fits of the data.
The guidelines were developed over the last two years in parallel with Butler’s newly released 2020 guidelines and have some overlap, specifically:

*Head measurements should begin prior to test initiation. The duration of pretest monitoring depends on the expected test length. In moderate-to-high K settings, measurements should begin at least 30 s prior to test initiation; measurements should begin several hours or more prior to initiation in less permeable settings.*

and

*Measurement of both the expected ($H_o^*$) and measured ($H_o$) initial displacements is required. These two quantities should be compared to assess the appropriateness of the nominal casing radius and, in rapidly responding systems, the relative speed of test initiation and the impact of transducer placement.*

This is a lesson that was learned through trial and error, particularly at Asylum Lake where approximately 50% of head recovery in the maximum vacuum slug tests can in approximately in 1 second. Communication delays between the computer software and water level logger yielded partial recoveries if data collection was not begun before test initiation.
FUTURE WORK

Based on the results of this study, it is recommended that continued field studies be conducted to conclusively determine whether a scale effect between estimated $K$ and slug size and estimated $S_s$ and slug size exists. In future work, single well and multi-well slug tests should be conducted not only in high $K$ aquifers, but in lower $K$ aquifers as well as in aquifers of more diverse sediment types. A larger and more diverse data set will lead to a better assessment of the relationship between estimated $K$ and slug size. Repeating slug tests at already tested sites would also provide a quality control component. Additionally, performing slug tests at well fields with deeper wells and shallower water tables allowing for a larger range of initial displacements for testing, and more importantly, performing tests in wells with gravel packs that may lead to erroneously high values from smaller displacement physical slugs will more clearly reveal whether there is a scale effect between estimated $K$ and slug size.
Appendix A

Aquifer Pumping Test SOP
Standard Operating Procedures: 
Asylum Lake 48 Hour Pump Test Guide

Purpose:
This SOP was written to provide HFC Aquifer Testing module instructors and teaching assistants (TAs) a best practices field guide for setting up, conducting, and taking down a 24 to 48 hour pump test. This guide was specifically written for pump tests conducted at Well Field 1 in the Asylum Lake Preserve in Kalamazoo, MI. However, this guide may be applicable for pump tests conducted at other locations. For any questions please contact the course instructor, field coordinator, or SOP author (Jay S. Kim, 224-622-9896, jaykim663@gmail.com).

Location Information:
Well field 1 (figure 1, APPENDIX III) is located approximately 800 ft. east of the Asylum Lake Preserve parking lot (S. Drake Rd., north of the WMU Parkview Campus). Well Field 1 contains 14 flush-mount monitoring wells, one pumping well (AL 183, enclosed in a large brown metal box). A USGS monitoring well (AL104, also in a large brown metal box) is near AL183 but will not be used. Please refer to Figure 2 for all of the well locations.

Set-Up
I.) One Week Before the Pump Test
TA’s should spend this week familiarizing themselves with all of the equipment to be installed and utilized during the aquifer pump test.

A.) Neatly unpack and confirm that WMU got all of the items listed on the packing list from In-Situ.
   • Please keep all of the boxes and packing materials. These will be used to ship the equipment back once the field camp ends.

B) Read all instruction manuals provided by In-Situ regarding rental equipment and software. Download links are listed below for equipment manuals and software to be used:


C.) Test ALL electronic equipment to ensure they are operational:
   1.) Make sure all In-Situ Level Troll cables (Photo C below) are intact, desiccant seals are attached and dry, and red cable tip protectors are attached to their respective hardware.
   2.) Power up the field camp laptop (provided to TAs by field camp coordinator), check if the laptop is fully charged, and install WinSitu and Virtual Hermit software.
   3.) Power up the In-Situ Rugged Readers and check to see if their batteries are charged. Test these by connecting a Level Troll 700 Unit to a Rugged Reader.

![Rugged Reader plus cables](image1)
![LevelTroll Cable Adapters](image2)
![100ft InSitu Level Troll Cable+LevelTroll 700](image3)
4.) Make sure all water level meters are in working. The equipment room also contains several different kinds of water level meters so it is highly recommended that the TA’s learn how to operate each one.

   a.) Check if water level meter batteries are dead (9 volt battery)
   b.) Testing can be done by dipping an activated water level meter into a graduated glass filled with drinking water from a nearby water fountain.

D.) Go over the well construction logs for the wells at Asylum Lake Well Field 1 to become familiarized with them.

F.) Take note the two different kinds of Level Troll Cable adaptors (Photo B). There is one with a USB end and another with a 9-pin serial port end. The adaptor with the USB end will go to the field camp laptop while the serial port adaptor will be used for the Rugged Readers

G.) Practice using rental equipment and software using instructions provided by In-Situ.

*InSitu will be switching to a smartphone iOS and Android app to program/monitor Level Trolls instead of Rugged Readers in the future. If this is the case, please update this SOP accordingly.*

II.) The Day Before the Pump Test (Step-Drawdown Test)

A.) Load items from APPENDIX I into the trailer in the morning.

B.) Send a group of students and the field camp coordinator to grab all of the equipment listed in APPENDIX II from the Department Pole Barn

C.) Pump Assembly for Step-drawdown Test and Aquifer Test:

1.) Carefully feed the narrow-probe water level meter into the pumping well. Use the small opening at the top of the cap sealing the pumping well. Be careful not tangle the probe around the pump. Take a static water level reading.

2.) Apply white Teflon tape to steel pipe threads to ensure water-tight seal

3.) Carefully use wrenches to twist on the first pipe for the pumping well assembly:

4.) Securely twist on second pipe that has the flow gauge to the first pipe while using wooden support blocks (found inside pump housing). Secure the pipes with monkey wrenches.

5.) Clamp on pump hoses so that they go 400ft NE towards Asylum Lake. Place a 50-gallon black plastic drum where the hose ends. Students will measure flow rate from the flow gauge at the pumping well and at the 50-gallon drum during the step drawdown test:
E.) Once everything is ready for the step-drawdown test, hand over control to the class instructor who will guide the students for the rest of the day. While the step draw-down test is occurring, proceed to install control well (AL111) pressure transducer:

1.) Send out TAs to control well AL 111 (Photo A) located along the sidewalk on Drake Rd. by the Asylum Lake Parking lot (see location of AL 111 in figure 1).

   a.) Photo B below lists the equipment to take: T-Handle Well opener, 1x InSitu LevelTroll 700, data cable, Rugged Reader, serial port adapter, water level meter, field notebook, and pen:

   b.) Installation of Control Well:
   i.) Open Steel well cover using T-Handle and take & record static water level for AL 111

   ii.) Record pressure transducer ***InSitu Level Troll 700*** serial number (see Photo C above for “S/N” location on pressure transducer)

   iii.) Carefully attach the pressure transducer to one end of the data cable. Attach the serial port adaptor to the other end of the data cable, then attach the serial port end to the Rugged Reader. **Save all red rubber tip protectors, desiccant caps, and twist ties.**

   iv.) Program in pressure transducer to desired parameters:
   a.) Add site name, well name, project name (eg. ASYLK, AL111, SUI PMPTST)
   b.) Set readings for **linear** time intervals (15 min intervals)
   c.) Set probe to measure “**depth-to-water**” (enter in recorded static water level)
   d.) Set probe to start automatically recording water level data one hour from insertion.

   vi.) Carefully lower the pressure transducer & data cable into AL111 with a water level meter following to keep track of pressure transducer depth. Use the following method below for an easy installation:

   **The Cascarano Method**
   a.) Have one person spooling down the data cable into the well with the water level meter probe following the pressure transducer to check for depth.

   b.) Have second person holding the water level meter above the person lowering the pressure transducer. Keep track of depth while the water level meter unwinds.

   c.) Lower pressure transducer **10 ft.** below the recorded static water level. The **Level Troll 700**’s cannot go below the water level they are rated for. The ones we order for the HFC have a max depth of 35ft below the water level. Going below this depth will result in the probes becoming damaged.
The Cascarano Method (Continued)

d.) Mark with a black marker (or colored tape) where the pressure transducer cable has stopped at top of the well casing.

e.) For all other wells, securely tape the pressure transducer cable to looped metal stakes that have been inserted into the ground adjacent to the well (see Figure 3).

vii.) Check Rugged Reader (still connected to data cable) to see if pressure transducer is giving proper readings (user will see live water level readings). If readings match the static water level, disconnect the Rugged Reader from the cable, attach desiccant cap to cable tip, and carefully coil remaining cable into well casing housing. Close the steel well cover.

G.) Once step-drawdown test is complete, pack up all equipment and securely lock into trailer before leaving Asylum Lake. Leave trailer overnight at Asylum Lake or drive back to Wood Hall.

III.) Morning of Pump Test

A.) Arrive at 8:30AM to set-up the pump test field site. Use Figure 2 as a layout guide. Students and instructor will arrive by 10:30AM to help.

1.) Figure 2 shows the locations of wells that will take pressure transducers and their associated cable lengths.

   a.) Any well in Figure 2 with a cable length # and a “RR” means the cable will not be run towards the trailer but will be programmed in via Rugged Reader.

2.) Use the “Cascarano Method” described above for installing pressure transducers. For data cables going to the Hermit network hub, refer to Figure 3 for the pressure transducer/data cable setup diagram.

   a.) Do not forget to record static water levels and record pressure transducer serial numbers for each well receiving a pressure transducer. You will need this data when setting up the pump test software. (Well ID, Pressure Transducer S/N, Static Water Level)

B.) Add fuel to and activate the small power generator, place next to the trailer door, use as a temporary power source for the field camp laptop until the main power generator is turned on.

*Make sure generator exhaust port is facing away from the trailer so that fumes do not go into trailer*

C.) Check to see if all the 5-Gallon gasoline cans are full then test the main power generator to see if it works.

D.) Try your best to neatly lay out pressure transducer cables to eliminate trip hazards around the trailer.

E.) Carefully connect the eight data cables to the In-Situ Network Hub (eight connections max), use the 50ft. data cable to connect the network hub to the USB adaptor then to the field camp laptop (Photo B, page 1).
Set up the trailer interior as pictured below:

Photo A: Interior table layout for trailer. Tape to the floor the data cable going from the laptop to network hub to reduce trip hazards.
Photo B: Closer look at the table layout. Virtual Hermit software is open on laptop.
Photo C: InSitu Network hub with 8 pressure transducer cables attached.
Photo D: Tent and trailer setup for pump test. Photo is facing East.

E. Separately install pressure transducers for wells AL139 and AL118 that will be programmed and activated manually using the Rugged Readers. Neatly coil any excess cable and attach desiccant caps to ends.

E.) Drop off a water level meter, clipboard, three water level data sheets, and time interval sheet at each well.

*Future pump tests may use an InSitu network hub that can take more than just 8 connections. If this is the case then AL139 and AL118 will be networked into the network hub. Please change SOP accordingly.

IV.) TA Instructions for Students

A.) Set up the tent and main power generator as seen in Figure 2.
   1.) Finish pressure transducer installation while students set up tent and generator. Have field camp coordinator direct students if needed.

   2.) Optional: leave one pressure transducer uninstalled to show students an installation demo.

B.) Laptop Instructions:
   1.) Turn on laptop, log-in (ask field camp coordinator for login password, write it down)
      a.) do not forget to check if laptop is plugged into a power source and is charging.

   2.) Open Virtual Hermit software, open the software manual to Chapter 2 “Getting Started” and go through with students the instructions to set up for the pump test:

3.) Some tips:
   a.) Give the pump test an easily recognizable name (e.g. HFC 2018 SUI Pump Test).

   b.) When clicking the ▶️ buttons in the “TROLL Setup Wizard” menu to search for COM ports, the program will temporarily freeze while it is communicating with the network hub, this is normal. Let the program run as-is for 5-10 min.

   c.) Have Well ID, Pressure Transducer S/N, and Static Water Level data information ready. You will be manually entering this information in for each pressure transducer.

   d.) Use the software to rename each pressure transducer from S/N to its associated well ID #.

4.) Some important parameters:
   a.) Pressure Transducer reference levels must be manually set since they only calculate the height of the water column above the sensor tip. Set to “depth-to-water” measurements.

   b.) Data recording time interval should be set as “true logarithmic” so that pressure transducers take as many readings as possible when the pump test starts.

   c.) Set the linear data recording time interval to one hour. Once a linear recording time interval is reached the pressure transducers will take one reading per hour.

   d.) Set the pump test for a manual start (pick a designated start time)

   e.) Set Virtual Hermit to download data every minute (this can be changed to any time interval later such as 15 minutes)

C.) Pump Test Start Instructions
1.) Have at least one student at each well. They will be taking manual readings. Also decide on a designated start time with the field camp instructor.

2.) Assign one student as a designated time keeper and air-horn blower. They will also need the time interval sheet and stopwatch.

3.) Have main generator fully fueled and ready to start. Assign one student to the pump activation switch. Ask them to wait for you to yell “Start!”

5.) Assign students to wells AL139 and AL118. Instruct them how to use the Rugged Readers to manually start the pressure transducers in wells AL139 and AL118 when they hear “START!”

6.) Hit the “Start” button in the Virtual Hermit program 1 minute before the designated start time. At the same time activate the main power generator
   a.) It will take a few seconds for the Virtual Hermit to send the start signal to all of the connected pressure transducers.

7.) Yell out “START!” at the designated start time so that the student can flip on the pump activation switch. At this point the power generator should be running. Let students take over manual readings.
D.) Once everything is up and running, run several three-outlet extension cables from the main power generator to the tent and another extension cable from the tent to the trailer. Plug in the laptop charger into this cable. Attach hang lights in tent and trailer.

E.) Most of the work is done for the TAs until the pump test ends. However, as the pump test progresses the TAs will have the following responsibilities:

1.) Babysit the pump test while students are in lecture.

2.) Periodically check pump test data on Virtual Hermit software and Rugged Readers
   a.) When switching to the “Real-time” tab the program will briefly freeze. This is normal.
   b.) Use the “Log Graph Tab” to look at drawdown data for all the pressure transducers.

E.) Remind students to record flow rate every 30-60 min to check for pump rate consistency.

1.) Record flow rate value before pump test begins ($Q_0$)

2.) Record flow rate value one hour after pump test begins ($Q_N$)

3.) Do: $(Q_N - Q_0)/60$ to find flow rate in Gallons Per Minute (GPM)

V.) Post Pump Test
A.) Pump Test Log Completion and Downloading Data Using Virtual Hermit Software:

1.) Once the signal is given to stop the pump test hit the “Stop” button in the Virtual Hermit software.

2.) Hit the “Export Data” button to export raw data. Follow steps to configure exported raw data.

3.) Download data using Win-Situ 5:
   a.) Open “Win-Situ 5” software on laptop.

   b.) When prompted to connect to a device hit “no” since the data has already been downloaded to the laptop from the Virtual Hermit.

   c.) Use the file explorer to the left to navigate to the folder containing pump test data
      i.) Folder name will assigned by the TAs for the pump test.

   d.) Each pressure transducer will have its own file. Right click on the file to open a pop-up menu, scroll down to “Export to CSV”.

      i.) CSV stands for “Comma-Separated Values” and is Microsoft Excel compatible.

      ii.) TAs and students will use Microsoft Excel to process the pump test data.

   e.) Exported CSV files for each pressure transducer will be located at the following location:
      i.) C:\Users\username\Documents\WinSitu Data\Exported Data\Pump Test Name

   f.) Copy and paste exported data into a flash thumb drive. Make sure to back up this data on other thumb drives.
B.) Getting Data from the Rugged Reader wells AL139, AL118, and control well AL111
1.) Manually stop readings using Rugged Readers for these pressure transducers.

2.) Download data into Rugged Reader.

3.) Hook-up Rugged Reader into laptop, use laptop to search for the pump test files in the Rugged Reader.

4.) Copy and paste pump test data from the Rugged Reader into:
   C:\Users\Username\Documents\WinSitu Data\Site Data\Pump Test Name

5.) Open files using Win-Situ 5 on laptop and export files to CSV format.

6.) Copy and paste exported data into a flash thumb drive. Back up this data on other thumb drives.

C.) Site Deconstruction
1.) Carefully remove pressure transducers from each well, dry them off, place on red rubber tips, neatly place back into boxes pressure transducers came in.

2.) Neatly coil data cables, add red rubber tips and desiccate tips to each cable, use twist ties to hold cables in place to prevent them from getting tangled.

3.) Neatly dismantle tent and store in trailer.

4.) Neatly wind up water level probes and store in trailer.

5.) Neatly pack/secure trailer with all other equipment. Bring back to Wood Hall and unload all equipment that will not be needed for the next module into the geoscience equipment room.

VI.) Conclusion

A smooth pump test that yields good data requires great coordination and communication between the TAs, students, and instructors; therefore, it is vital the TAs and instructors are well prepared for this complex field activity. Additionally, not all pump tests go smoothly. Therefore, everyone involved must aware of the problems that can occur in the field such as equipment malfunction, bad weather, lack of student participation, theft, animal attacks, etc. Therefore, stay responsible, tread carefully in the field, do not panic, and calmly deal with the problem if one arises. Finally, it is highly encouraged to add and improve this field guide as equipment and software advances with time, better field methods are discovered, and new problems (and their solutions) are encountered during future pump tests.
APPENDICES

APPENDIX I: Materials From Equipment Room:
- 15-16x Clipboards with storage space (to keep water tape log paper dry from evening dew)
- 14x Water Tapes with normal sized probes (varying brands from In-Situ, Heron, etc.)
- 2x Solinst 100 ft Water Tapes with thin probes
- 1x Water Tape with narrow probe (to be inserted into narrow opening at the top of pumping well AL183)
- Tent (Tarp, poles, bungee cords, stakes, ratchets, mallets)
- T-Shaped Bar (for opening square peg well covers)
- 2-3 Black & Decker Ratcheting Ready Wrench (black wrench with orange circles at tips, contains multiple ratchet sizes)
- 2 Drinking Water Coolers
- Office Supplies (Duct tape, Sharpies, pens, etc.)
- Small portable gasoline power generator
- Marking Equipment (Caution tape, fiberglass orange poles, mini flags)
- 3 Hang lights
- 2 Hanging Power Strips
- 2x Three plug extension cords
- 11x In-Situ Level Troll 700 Pressure Transducers (plus red nipple caps)
- 1x 50ft In-Situ Data Cable (plus red rubber tips and desiccant tip)
- 8x 100ft In-Situ Data Cables (plus red rubber tips and desiccant tips)
- 3x 200 ft In-Situ Data Cables (plus red rubber tips and desiccant tips)
- 2x In-Situ Rugged Readers plus cases and cables
- 1x In-Situ Rugged TROLL Net Hub (grey box, aka the Hermit)
- 2x Cable to Rugged Reader Data Transfer Cables
- 1x Cable to USB Data Transfer Cable
- 3x Folding Tables
- Laptop with Virtual Hermit and Winsitu 5 software installed
- 3x large monkey wrenches
- 2x socket wrench sets

APPENDIX II: Materials from Pole Barn
- Large portable gasoline power generator
- Pump discharge water hoses (3x)
- 6x five gallon gasoline jugs
- Pump flow gauge and connector pipes
- Plywood board (for sound barrier)
- 50 gallon black plastic rain barrel
APPENDIX III: Figures

Figure 1: Map of Asylum Lake Preserve HFC Field Site including Well Field 1 Location (Modified from Google Earth)

Figure 2: Map of HFC pump test site with corresponding wells. Blue numbers indicate In-Situ Cable lengths to be used (in feet). Locations of trailer (TRLR), tent (TENT), and power generator (GEN) are highlighted in boxes on map.
Figure 3: Setup for pressure transducer cables going to InSitu Hermit network hub in trailer.

Figure 4: Table showing specifications for all wells in Asylum Lake Well Field 1
Appendix B

Reeves et al. 2020 *Groundwater* Paper
Pneumatic Slug Manifold Design and Practical Considerations

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Article Impact Statement: Simple, non-commercial pneumatic slug manifold design for standard 5 cm (2 in.) monitoring wells that is easy to replicate and assemble.
Introduction

Accurately determining the spatial distribution of hydraulic conductivity is essential for understanding the movement of groundwater and contaminants within subsurface flow systems. Slug testing is the most widely used method for estimating in-situ hydraulic conductivity, and is the preferred method for characterizing contaminated sites where pumping tests would incur additional expenses associated with treatment of the pumped water. Slug tests are single well hydraulic tests that perturb water levels within a well. The water level can be changed by adding or removing a slug in the form of a solid object, water, or air and monitoring the recovery to the pre-test, static water level. Hydraulic conductivity of the porous medium is then estimated by fitting the response data to analytical solutions (Butler 1998).

Pneumatic slug testing provides several advantages over physical slugs. First, pneumatic methods greatly exceed the ability of solid slugs to generate perturbations that extend beyond the disturbed zone-gravel pack of a well and ensure that measured responses represent the aquifer properties. The size or initial displacement of a pneumatic slug is proportional to differences in air pressure between the atmosphere and the inside of the well. This allows considerable flexibility as initial displacements can be selected along a continuum ranging from small perturbations equivalent to small solid slugs up to a maximum. Maximum displacements are defined by the distance from either (1) the top of the water column down to the top of the well screen for positive pressure tests, or (2) the top of the well screen up to the top of the well casing for negative pressure (vacuum) tests. Note that the positive and negative pressure designations are relative to gauge pressure where atmospheric pressure is equal to zero. The maximum displacement for positive pressure slugs depends on the degree to which a well can be pressurized. Wells in arid regions may have considerable distance between the top of the well casing and the water column. For these cases, the theoretical upper limit for a negative pressure test is the vacuum pressure at which water transitions from the liquid to vapor phase – an atmospheric pressure of
1 atm (101 kPa) amounts to an equivalent slug displacement of 10.3 m. Based on our experience, maximum displacements achieved in 5.1 cm (2 in.) observation wells are closer to 8.5 m due to imperfect pump efficiencies. Second, pneumatic slugs provide the closest approximation that is practically possible to the instantaneous water level change assumption used in all analytical slug test solutions (Hvorslev 1951; Butler 1998). For this reason, pneumatic slug data are typically cleaner and exhibit less noise than solid slugs (Figure 2). Near-instantaneous water level changes are particularly well suited for characterizing highly conductive aquifers with rapid recovery. Lastly, pneumatic slugs only require a pressure transducer and cable to be in contact with contaminated water, simplifying decontamination where required.

Despite the heavy reliance on slug testing for estimating hydraulic conductivity at contaminated sizes, pneumatic slugs are underutilized in the environmental industry. In this article, we present a simple, non-commercial pneumatic slug manifold design for standard 5 cm (2 in.) monitoring wells that is easy to replicate and assemble.

**Pneumatic Slug Manifold Design**

The pneumatic slug manifold design, along with annotated parts, is shown in Figure 1. The parts required for assembly of one unit include:

- 3 – 5.1 cm (2 in.) x 3.2 cm (1.25 in.) K packers,
- 3 – 5.1 cm (2 in.) x 3.2 cm (1.25 in.) nipples,
- 1 – 5.1 cm (2 in.) x 3.2 cm (1.25 in.) coupling,
- 2 – 10.2 cm (4 in.) nipples,
- 1 – 5.1 cm (2 in.) G tee,
- 1 – compound positive-negative pressure gauge,
- 1 – 5.1 cm (2 in.) ball valve,
• 1 – standard Schrader valve,
• 1 – 0.6 cm (0.25 in.) brass valve,
• 1 – 0.6 cm (0.25 in.) brass nipple,
• 1 – 2.5 cm (1 in.) cable grip, and
• 1 #5 [2.7 cm (1-1/16 in.) top and 2.2 cm (7/8 in.) bottom] white silicone rubber stopper.

All threads in the design adhere to National Pipe Thread Taper (NPT) standards, and Teflon tape is applied to all threads to ensure air-tight connections. Total parts cost of the assembled unit in Figure 1 is approximately $180 USD.

Commercially available alternatives also exist, but the design presented above has the following advantages: no modifications or changing of parts are necessary to switch between positive pressure and vacuum slug tests; the nipples and valves facilitate the use of vacuum pumps and air compressors for versatility in displacement size and direction; a series of three k packers is used at the base to effectively seal the well; metal components ensure a high degree of durability, and perhaps more importantly, can safely accommodate any practical pressure range used for pneumatic tests; and the parts are economical. The design is inexpensive and simple, and can be modified according to personal preferences and available hardware. For example, the use of brass is not necessary for the nipples and ball values, yet that is the most common material for these parts.

Three components – Schrader valve, 0.6 cm (0.25 in.) brass nipple, and compound gauge – require drilling followed by use of a tap to generate NPT threads in the 5.1 cm (2 in.) × 10.2 cm (4 in.) nipples at the locations denoted by purple boxes in Figure 1. These three components must have direct access to the air column to pressurize, depressurize, and measure pressure within the well, respectively. Installing each component necessitates a slightly different procedure:

• Schrader value – 0.5 cm (3/16 in.) drill hole drilled followed by a 0.6 cm (1/4 in.) NPT tap,
- 0.6 cm (0.25 in.) ball value – 0.5 cm (3/16 in.) drill hole drilled followed by a 0.6 cm (1/4 in.) NPT tap, and
- pressure gauge – 0.6 cm (1/4 in.) drill hole followed by a 1 cm (3/8 in.) NPT tap.

The Schrader valve is compatible with air compressor fittings to pressurize the monitoring well using either an air compressor, pressurized air tank, or hand pump. The 0.6 cm (0.25 in.) ball value and nipple are ideal for connecting 0.6 cm (0.25 in.) inner diameter tubing to a small vacuum pump.

**Practical Considerations**

The primary purpose of a pneumatic manifold is to provide a seal between the inside of the well and atmosphere and to facilitate a near instantaneous pressure release at the start of the test. Any impedance in air flow through the manifold at the start of the test decreased the quality of the test data. The large ball valve used in the design is essential for allowing air to rapidly enter or exit through the manifold. For a manifold where all threaded components are properly installed, the most common air leakage points are between the stopper and the transducer cable, or between the K packer and the well casing. A pressure transducer cable is the only piece of equipment that passes through the manifold, and a 0.6 cm (1/4 in.) hole is drilled through the center of the stopper and a single radial slot extending from the drill hole to the outside of the stopper is added to facilitate cable insertion. Once the transducer is positioned, tightening of the cable grip bolt deforms the silicon stopper and forms an airtight seal around the transducer cable.

K packers are suitable for sealing the well for negative and positive pressure tests, and the manifold design has been tested successfully to pressures of 240 kPa. Three K packers are included in the design although experience indicates that only two K packers are often needed to create the desired seal with the well; the third packer is included to accommodate maximum displacement tests. Despite the ability
of the manifold to generate larger slugs, we recommend constraining maximum slug displacements to 6 m for hydraulic testing purposes.

The manifold is designed specifically for 5 cm (2 in.) diameter monitoring wells, which is the standard diameter for monitoring wells in the United States. For different diameter wells, the simplest alternative is to use a Fernco coupling or similar flexible seal to attach a 5 cm diameter well casing section into a larger well casing, such as 10 cm, 13 cm, or 15 cm. Another design modification could be substitution for the Teflon tape at sites where contamination by per- and poly-fluoroalkyl substances (PFAS) may be a concern. A final design consideration is that the manifold could potentially pop out of the well at high pressures and cause injury. As an extra safety precaution, the manifold should be secured to the well housing (or other immovable object) during high pressure tests.

Limitations and potential sources of error can be introduced during pneumatic slug testing. Unlike solid slugs, pneumatic slugs cannot be used in wells that are screened across the water table as the air will be either pulled from the unsaturated zone during vacuum tests or pushed into the unsaturated zone during positive pressure tests. This will be apparent in the field as wells screened across the water table cannot be pressurized. We have also experienced monitoring wells (typically aged) screened below the water table that do not pressurize. At these wells, air is likely dissipating around leaky joints or cracks in the casing. Rotating the top casing segment clockwise has alleviated leakage in some cases, allowing the well to maintain pressure during pneumatic slug testing. Cracks in the casing can be confirmed using a downhole camera.

Discrepancies may exist between slug size or initial displacement based on gauge pressure and recorded water level data. The most obvious cause of this discrepancy is the limited accuracy and precision of the manifold gauge. In the case of positive pressure, a held-held digital gauge can be used to more precisely and accurately measure pressure at the Schrader value. A similar vacuum pressure gauge could potentially be incorporated into the tubing connecting the manifold to the vacuum pump via a T-
connector or splitter. Pressure values for each test should be recorded and compared to initial
displacements measured by the pressure transducers. Pneumatic slugs are balanced by a change in
water level within a well, and volumetric changes in the water column must be accompanied by water
flow out of the well and into the aquifer for positive pressure tests, or into the well from the aquifer for
negative pressure tests. Therefore, after changing the pre-test air pressure in the wellhead, the gauge
pressure should be allowed to equilibrate before opening the ball valve to initiate the slug test. The time
required for pre-test equilibration depends on the hydraulic conductivity of the formation.

Conclusion

A durable and easy-to-build pneumatic slug manifold design is presented and accompanied by a
detailed parts list. The design has been used by the authors over a diverse set of monitoring well designs
and hydrogeologic settings with hydraulic conductivity ranging from $10^{-3}$ to $10^{-8}$ m/s. Design
considerations, including potential modifications, and practical guidelines for pneumatic slug testing are
provided. It is our hope that this article will increase awareness of the applications and benefits of
pneumatic slug testing.

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Figure Captions

Figure 1. Pneumatic slug manifold. Purple boxes denote locations of requiring pre-drilled hole followed by tap to create NPT threads.

Figure 2. AQTESOLV plot of water level data (black squares) for pneumatic slug (vacuum) performed in a glacial outwash aquifer using the pneumatic slug manifold in Figure 1. The blue line represents the best-fit KGS (Hyder et al. 1994) analytical solution.
Appendix C

USB Organization – List of Raw Data and Analyses

I. Aquifer Pumping Test

   a. Aquifer Pumping Test Data

      i. SII Raw Data

          1. Pump Test

              a. Well AL101

              b. Well AL118

              c. Well AL127

              d. Well AL128

              e. Well AL139

              f. Well AL145

              g. Well AL164

              h. Well AL169

              i. Well AL173

              j. Well AL175
k. Well AL176
l. Well AL178
m. Well AL182
n. Well AL184
o. Well AL1318

2. Recovery

a. Well AL101
b. Well AL118
c. Well AL127
d. Well AL128
e. Well AL139
f. Well AL145
g. Well AL164
h. Well AL169
i. Well AL173
j. Well AL175
k. Well AL176

l. Well AL178

m. Well AL182

n. Well AL184

o. Well AL1318

b. Aquifer Pumping Test Analysis

i. Pump Test Analysis

1. Well AL101

2. Well AL118

3. Well AL127

4. Well AL128

5. Well AL139

6. Well AL145

7. Well AL164

8. Well AL169

9. Well AL173
10. Well AL175

11. Well AL176

12. Well AL178

13. Well AL182

14. Well AL184

ii. Recovery Analysis

1. Well AL101

2. Well AL118

3. Well AL127

4. Well AL128

5. Well AL139

6. Well AL145

7. Well AL164

8. Well AL169

9. Well AL173

10. Well AL175
11. Well AL176

12. Well AL178

13. Well AL182

14. Well AL184

c. Aquifer Recovery and Pump Test Analysis Summary

d. Distance Drawdown Data and Analysis

II. Slug Tests

a. Asylum Lake

i. Multi-Well Slug Tests

1. Data

   a. Test 1

   b. Test 2

   c. Test 3

   d. Test 4

2. Analysis

   a. Test 1
b. Test 2

c. Test 3

d. Test 4

ii. Single-Well Slug Tests

1. Data

   a. Well AL101

   b. Well AL182

2. Analysis

   a. Well AL101

   b. Well AL182

b. Grand Rapids

   i. Data

      1. Well 4s

      2. Well 4d

   ii. Analysis

      1. Well 4s
2. Well 4d

c. Muskegon

   i. Data

      1. Well MW3I
      2. Well MW4I
      3. Well MW5I
      4. Well MW6I
      5. Well MW8I
      6. Well MW9I
      7. Well MW10I

   ii. Analysis

      1. Well MW3I
      2. Well MW4I
      3. Well MW5I
      4. Well MW6I
      5. Well MW8I
6. Well MW9I

7. Well MW10I

III. Asylum Lake Drillers Logs
Appendix D

Equipment List

1. 100 ft In Situ Inc Water Level Meter
2. Pneumatic Unit
3. 150 Psi Craftsman Maintenance-Free Air Pump
4. 2 ft Displacement Midwest Geosciences Physical Slug and rope
5. In Situ Inc USB Troll Com Cable Connect
6. In Situ Inc Level Troll 700 and 200
7. Allegro Industries Rotary Vane Sampling Vacuum Pump
8. Dell Field Computer
9. 100 ft In Situ Inc Rugged-Poly-Vented Cable
10. Write in the Rain Field Notebook
11. Well Key
12. Generac iQ 2000 Generator
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